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| 13. ABSTRACT (Maximum 200 words) The principal goal of the present study has been to construct and test computer algorithms for fluvial sediment erosion and deposition processes. Real-life topographic features in arid terrain have been used as a source of groundtruth information. Much use is being made today of generic landscape evolution models. But little effort has gone into testing such models against actual landscape evolution as measured in the field. In particular, modern landscape models are seldom used for site-specific studies. This work has attempted to bridge that gap. The near-term objective has been to test some commonly used constitutive rules for sediment transport against geomorphic evidence as observed in the field. The present work has focussed on defining broad scale erosion/deposition patterns to fluvial erosion patterns. These comparative studies are critical for transferring generic sediment transport rules used by most landscape modelers into actual hands-on algorithms that can be used in real life situations of interest to the Army. We have also been interested in applying our studies of desert pavement to problems of Army interest, in particular, to possible ways to restore or stabilize these ancient surfaces. An ancillary goal has been to understand the problems involved in scaling-up fundamental, small-scale sediment transport physics to large-scale engineering and environmental applications involving erosion and landscape change with time, and to develop computational tools appropriate for such large-scale applications. | | | |
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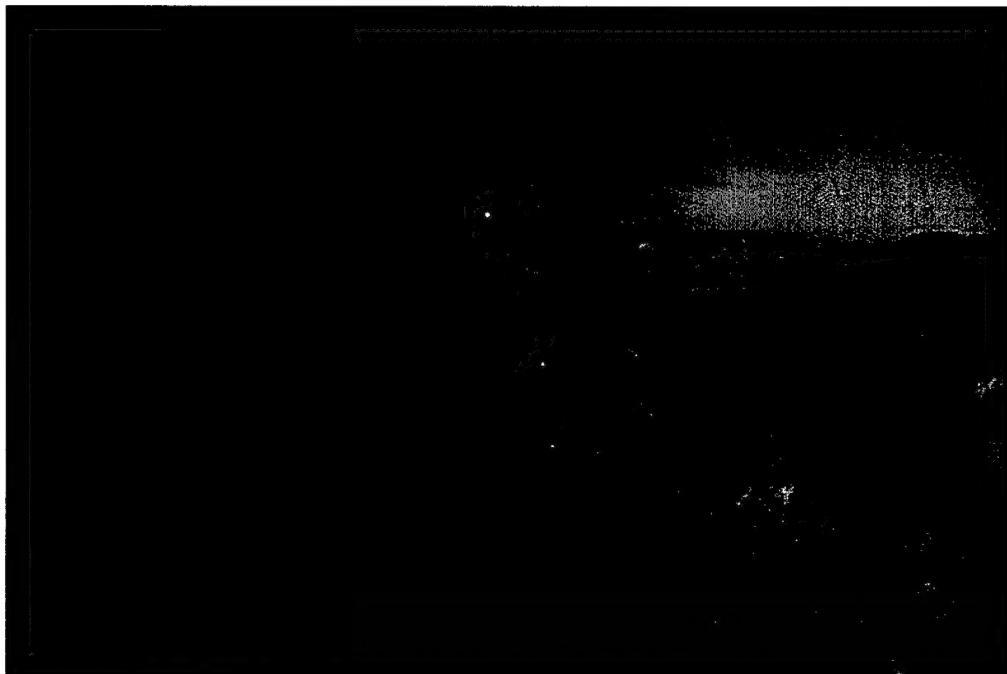
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1998**

Discrete Methods for Sediment Transport Modeling (30685-EV)



View Toward Ft. Irwin, CA, from Soda Mountains

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Memorandum of Transmittal

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Research Objectives:

The principal goal of the present study has been to construct and test computer algorithms for fluvial sediment erosion and deposition processes. Real-life topographic features in arid terrain have been used as a source of groundtruth information. Much use is being made today of generic landscape evolution models. But little effort has gone into testing such models against actual landscape evolution as measured in the field. In particular, landscape models are seldom used for site-specific studies. This work has attempted to bridge that gap. The near-term objective has been to test some commonly used constitutive rules for sediment transport against geomorphic evidence as observed in the field. The present work has focussed on defining broad scale erosion/deposition patterns to fluvial erosion/deposition processes. These comparative studies are critical for transferring generic sediment transport rules into actual hands-on algorithms that can be used in real life situations of interest to the Army.

We have also been interested in applying our studies of desert pavement to problems of Army interest, in particular, to possible ways to restore or stabilize these ancient surfaces.

Approach to Problem:

1. Erosion studies were carried out through a combination of computer simulation and field studies. Computer simulations of hillslope transport were performed for sites where fluvial erosion and deposition are important, ongoing, and where field observation could provide suitable feedback for improving and refining the model. We modeled specific geographic sites, not generic landscapes. Field sites chosen were in the Mojave Desert on terrain units of the type that commonly occur in military training areas. Thus most of the work was focussed on the granitic dome/pediment surfaces in the Cima Dome, CA, area that resembles in many respects granitic terrains found extensively at Fort Irwin.,
2. Field work was carried out to provide feedback to model development. Field investigations pinpointed particular location-specific processes indicated as a result of modeling, and identified characteristic regions of erosion and deposition that could be checked against model output. Using electronic survey equipment acquired through ARO resources, detailed hillslope transects were made in the Mojave Desert. Computer simulations of hillslope transport was performed for a variety of different sediment transport rules. These comparative studies were used to test sediment transport rules for use in specific terrain situations.

3 . Studies of processes on, and stability of, desert pavement surfaces have been pursued via long-time-based observational studies. Desert pavement is a commonly occurring desert surface that is widely used (e.g., at Yuma Proving Ground) for military vehicle traffic. Field experimentation involving disturbance of pavement surfaces has been continued in order to understand recovery processes where the disturbances heal themselves, or to understand why surface disruption provides a positive feedback loop that leads to further unraveling of pavement surfaces. Pavement studies have been mainly field based so far, but it is anticipated that modeling studies will be initiated as the result of the studies performed here.

Significance Of Research Results For US Army:

i) *Large-Scale Erosion Studies*: These methods have been developed for use on a PC, and can be applied to large geographic areas of interest to both civilian and military land-use managers. The simulations have been run on areas of over 100 square kilometers, and are applicable to NTC, YPG and other regions of comparable size, Figs. 1 and 2. Runoff is tracked over the entire geographical region of interest, Fig. 3. Regions of erosion and deposition can be determined quickly, Fig. 4, and the magnitude (thickness) of eroded and deposited sediment computed. The model can run in an asynchronous mode whereby individual storms can activate flow in a subset of available drainage channels in the study area. The model is thus applicable to sedimentation resulting from a single localized storm, Fig. 5. Because slope is a central factor in all sediment transport rules, slope maps are useful for an intuitive assessment of regions likely to show serious erosion or deposition, Fig. 6. On a smaller scale, the model will be useful for assessing the effects of fluvial sedimentation and erosion resulting from land-use practices such as construction of roads, berms, soil compaction and so on. It is clear that digital data must be available that is sufficiently accurate in terms of both vertical and lateral resolution to enable an accurate determination of hydrologic flow directions to be obtained. A present limitation in implementing the model is the lack of adequate digital topographic data in regions of low slope typical of areas where vehicle-based training and testing is performed.

Accurate assessment of erosion rates is a critical national need. For example, the Yucca Mountain Nuclear Waste Disposal Site in Nevada has been chosen partly on the basis of assumed low erosion rates. Proposed expansion of the US Army's Fort Irwin training facility in California requires knowledge about the response of landscape, including erosion, to new types of land use. Modern attempts to simulate the evolution of landscape in response to erosion by running water have so far mostly been aimed at geological reconstruction of existing landforms. But the technical capability to apply such methods to prediction of future changes in landscape is rapidly maturing. The present study has constructed a

basis for understanding what limitations exist in scaling basic physical measurements to field scale problems.

ii) *Hillslope Studies*: It is of importance to all land managers, including the Army, to be able to assess the future behavior of specific terrain units to human impact of various kinds. Detailed field studies of representative terrain units, such as the small Mojave Desert hillslopes studied here, are necessary to identify and quantify the geomorphic processes that may affect terrain response to disturbance. Our studies have helped to distinguish between those processes that are likely active under today's climate regime from those that have been operative under past climate regimes. This kind of investigation is critical for assessment of landscape response to human activity.

iii) *Advection And Diffusive Models*: Landscape evolution models are an essential part of the tool box of landscape management. Most such models (except for some specialize models used in agricultural studies) are generic, in the sense that they purport to indicate the general *kind* of change that can be expected in landscape over some period of time (usually a time of geologic interest). Our studies of advective and diffusive sediment transport models are aimed at calibrating such models against field conditions for specific arid terrain sites of the type of interest to the US Army. Our studies at Cima Dome represent an exercise of the model in a setting similar to that found at locations in nearby Fort Irwin.

iv) *Long-Time-Based Studies of the Stability of Gravel Surfaces (Desert Pavement)*: Armored gravel surfaces are ubiquitous across much of the southwest US, including Army reservations at Fort Irwin and Yuma Proving Grounds. Disturbance and destruction of these surfaces, mainly by vehicle traffic, is widespread. Our long-time-based studies of controlled disturbance of desert pavement surfaces in the Mojave Desert have identified some of the mechanisms responsible for pavement development and stability, and hence suggest strategies for restoring disturbed surfaces to an approximation of their original form. This should be of considerable interest to the Army, both for reasons of environmental stewardship, as well as for the purpose of maintaining training surfaces in something like their original condition.

v) *The Dynamics Of Cryptogamic Crust on Gravel Surfaces*: Cryptogamic soil is a biologic crust that forms over large areas in the Mojave Desert and Basin and range area, and consequently is found commonly on arid military lands. The occurrence and motion of cryptogamic soil islands on otherwise bare gravel patches appears to be a result of orientation and edge effects associate with soil-island geometry. The interaction of such islands with vehicular or foot traffic has not been studied, but it is clear that disturbance of the island perimeter by human activity is likely to have a large effect on the stability of the soil surface.

Army efforts to maintain existing surface conditions on land under Army control depends on the ability to identify and understand the nature of such surface features and processes.

vi) *Predictability in Geomorphology*: Assume that a rigorous, physically-based model has been developed for use in landscape evolution studies. The Army wishes to use this model for purposes of land management. Can management decisions be based upon the outcome of predictions based upon this model? Our studies suggest that the answer is probably "no", if one is talking about site-specific predictions where the model is used without strong attention being paid to the geologic record and to previous experience either at the site in question or at similar (analogous) sites. Also, even with an otherwise good physical model, uncertainties in the actual configuration of soils, bedrock exposure, particle size, vegetation distributions, etc., can render the model ineffective. Our studies have suggested practical strategies for overcoming such inadequacies in model application – such as the incorporation of feedback loops in predictive schemes. These results could have a potentially significant impact on Army land management practices.

Accomplishments:

Development of Physically Based Sediment Transport Model: The discrete computer model WATERBOT has been developed. A simplified flow-diagram is shown in Fig. 14. The model tracks hydrologic "marker particles", Fig. 7, as they move downslope, employing an accompanying sediment transport rule to drive erosion and deposition processes on the chosen surface. The topographic data sets typically used to run the model are USGS 30 meter DEMs. The model correlates rainfall patterns to patterns of erosion and deposition. Adjacent 7.5' quadrangles can be joined into a single map for use in WATERBOT; thus the model is suitable for large scale applications. It is feasible to simulate sediment transport over the area covered by as many as six or more 7.5' quadrangles. WATERBOT is a PC-based model written in FORTRAN.

Model Indicators of Areas of Erosion and Deposition: WATERBOT can be used to study erosion and deposition of sediment across large geographical areas. Fig. 4 shows computed areas of erosion (blue) and deposition (green and yellow) on an area measuring about 10 km on a side. The location is in the Cima Dome area, Mojave Desert, California. On pediment surfaces such as Cima Dome or geomorphically equivalent surfaces in areas such as NTC, zones of erosion generally indicate that bedrock is at or near the surface, while zones of significant deposition generally indicate that the surface is lose alluvium. These correlations are *prima facie* indicators of both surface characteristics and load bearing ability. Thus yellow zones in Fig. 4 can be expected to be areas in which

surface mobility for wheeled vehicles will be degraded, while blue zones generally indicate a firm surface.

Model Indicators of Zones of Sediment Accumulation: The model shows how modifications of surface topography can induce local zones of erosion and deposition. Topographic barriers to downstream runoff are shown to produce upstream zones of sediment accumulation, Fig. 8. These sediment accumulation zones are seen in the field where natural flow deflectors such as cinder cones have interfered with surface runoff from higher elevations. Modern artificial barriers also exhibit this behavior, as seen in the sediment trapping upstream of freeway flood control berms, Figs. 9 and 10.

Model Indicators of Zones of Enhanced Erosion: Surfaces that have low rates of intrinsic erosion lead to runoff of "clear" water that produces enhanced erosion downslope as soon as it reaches a more erodible substrate. Model studies of natural low-erodibility surfaces such as some lava flows show striking erosion features downslope, Fig. 11. Similar behavior occurs whenever terrain surface properties are modified to increase run-off (such as by compaction) or to decrease erosion (as occurs when a surface is covered with concrete or other erosion resistant material, Fig. 8). The WATERBOT model provides a way to envision the possible erosion and deposition side effects that may accompany artificial landscape modification.

Hillslope Diffusion: Hillslope diffusion represents that set of natural surface processes such as soil creep and rainbeat that delivers sediment from unchanneled hillslopes to local drainages. Diffusion tends to smooth surfaces. Diffusion represents the main set of natural processes that will over time eliminate the presence of man-made surface disturbances that are not destroyed by channelized flow. Our studies have looked at the rate at which diffusive processes must operate to remove irregularities on the surface imposed at a given rate. By considering the simultaneous function of two otherwise independent diffusion processes, the smoothing effect can be quantified in terms of observable density of disturbances, such as impact crater or road berms.

Presently Inactive Hillslope Processes: Fine-scale geomorphic mapping of a hill in the Mojave Desert has identified at least half a dozen transport mechanisms that are, or have been, important in hillslope evolution – earth flows, slumps, animal burrowing, dry ravel, boulder role, and overland and channel flow. Age information regarding timing of these processes is inferred from desert varnish characteristics. Some of the identified processes, such as earth flows, are probably early Holocene or late Pleistocene. This implies that the modern hillslope configuration – its slopes, soil thickness (which was measured by seismic transects), clast distribution and so forth – is at least partly a product of processes that are no longer operating today. This suggests that "recovery" of a

surface from anthropogenic disturbance may not converge toward existing undisturbed surfaces , since those surfaces may not be a product of presently occurring processes.

Advective Processes: Advective sediment transport processes are those mediated directly by running water. Comparison of advective sediment transport with field surveys that determined regions of erosion and deposition showed that in some cases good agreement could be obtained between theory and observation, but that in other cases, agreement between surveyed surfaces and modeled regions of erosion and deposition was poor. Gullies developed on the artificial embankment of Fig. 12 could be modeled with standard sediment transport laws, but some natural gullies, Fig. 13, could not be modeled with standard sediment transport power-laws. Further work is needed in this area, but our results suggest the limitations of some commonly used transport laws.

Predictability in Geomorphology: Studies in uncertainty of prediction in geomorphology and sediment transport have been developed. This work provides guidance for organizations, including the Army, who need to make specific recommendations for land use management. The results of the study identify a number of factors that contribute to errors and uncertainty in predicting the future behavior of large natural systems such as landscapes. The role of uncertainty in geomorphic systems is a tricky one, and its study is potentially controversial. The results of our studies show not that prediction is not possible, but that attempts at *site-specific* prediction – a prediction mode of substantial interest to organizations like the Army – is not likely to be possible on the basis of mathematical modeling alone. Rather, use of analogy, and reliance on the historical and geological record, is likely to be at least as important as the use of quantitative mathematical models. Further, prediction may be limited by our lack of knowledge of the present state of the system – an observation which suggests that resources might be more effectively applied to instrumentation and data gathering than to improvement of computational models.

Long-Time-Based Studies of the Stability of Gravel Surfaces: A long-time-based study of diffusion on desert pavement has been continued, detailing the dynamics of the these important desert surfaces. This worked focused particularly on the response of surfaces to controlled human disturbance. The results of long-time-based studies of changes on desert pavement surfaces show clearly that these surfaces, although stable over millennia, are not static, but rather exist in a state of dynamic stability. Repeat photography shows how animal activity and other agencies is effective at creating a continuing dislodgment and transport of small surface stones, even on flat surfaces. This dynamical background of activity is an essential ingredient in the ability of pavements to repair disruptions of their surface. As discussed below, this observation, and the measurement of clast

size, areal densities, and other surface parameters, provides a scientific basis for approaching the problem of stabilizing or rehabilitating artificially disturbed desert surfaces. This work is of potential value for Army efforts to remediate and restore desert landscapes that have been disturbed by vehicle traffic or ordnance impact. This work is preparatory to planned future controlled studies at Yuma Proving Ground of the response of natural landscape to anthropogenic disturbances.

The Dynamics Of Cryptogamic Crust on Gravel Surfaces: The occurrence of natural dynamical changes in arid terrain surfaces needs to be understood as part of a larger program to assess the role of human disturbance in landscape behavior over time. These studies of the influence of cryptogamic crusts on the form of desert pavement surfaces in the northern Great Basin indicates that significant biological activity is associated with pavement surface in this climatic regime, which may be contrasted with the modern pavements in more arid regions such as YPG and NTC. In climates where cryptogam is an important component of the soil ecology studies of cryptogam-associated surface stability represent an important baseline conservation or restoration studies. It is important to understand the nature of the cryptogamic crust since pavements further south may have formed under climatic regimes that resembled those found now only at more northerly latitudes, where cryptogamic soils are well-developed.

Technology Transfer:

Yuma Proving Ground (YPG): Communications between the PI and YPG (Ms. Valerie Morrill) have been established regarding application to problems at YPG of some of the ideas on landscape processes developed under the present proposal. Two trips to YPG by the PI and graduate student Lonny Boring have given us an introduction to the local terrain and to some of the problems facing environmental managers there. Talks were presented by the PI and Boring to base personnel. Time was also spent in the field with David Lashley of WES. It seems clear that our analysis of pavement surface processes can be of use to the general problem of the origin, nature and age of the various pavement and fan units being studied by Lashley. We have also made a formal presentation of some of our work to YPG personnel. We have submitted a proposal for further investigation of disturbance by Army traffic of desert pavement surfaces at YPG. We will assess the construction of experimental plots on disturbed areas of desert pavement in an effort to better understand the problem of pavement degradation and destruction. Experimental plots that were graded, raked or otherwise smoothed, and which were seeded with appropriate populations of stone sizes would provide, over a few years, important information on stability and potential for restoration for desert pavement surfaces.

Construction Engineering Research Laboratory (CERL): The PI presented a talk at a CERL workshop in Urbana. Conversations were held with Bill Goran about interest of CERL in landscape modeling and surface process studies and restoration and maintenance of disturbed lands. The work on gravel surface dynamics described above is a point of common interest.

Waterways Experiment Station (WES): The PI attended two workshops on vehicle terrain interaction, and presented talks on how the particle dynamics method could be applied to traction problems. The PDM method seems optimized to treating that difficult zone at the boundary of tread or wheel and soil where the engineered precision of the vehicle meets the undesigned complexity of the soil.

Zzyzx Workshop: The PI and graduate student Lonny Boring attended week-long workshop at Zzyzx CA on "New Research Directions in Desert Surficial Processes and Landscape Dynamics on Military Lands". The PI made a presentation on modeling work carried out under the present project. At this meeting previous phone interactions with Dr. Fred Brieuer of WES were further developed. Dr. Brieuer is interested in the archaeological implications of various surface features found on the YPG pavement surfaces, while our expertise lies in a knowledge of natural surface processes on pavements. Important synergies are anticipated in combining our expertise with that of Dr. Brieuer. We anticipate collaborating on future work at YPG. Similar discussions were had at Zzyzx with David Lashley, also of WES, with the idea of correlating our ground based analysis of surface processes with Lashley's spectrographic work regarding classification of distinct pavement units.

Computer Program: The WATERBOT program is being actively used to study erosion/deposition processes on arid land surfaces. It is anticipated that this program will become available to Army personnel. The program is written in FORTRAN and runs under Windows NT on a PC. A copy of WATERBOT appears in the Appendix.

Figure Captions

Fig. 1. Photograph of pediment area at Cima Dome similar to areas at Fort Irwin used for training purposes.

Fig. 2. Shaded relief map of Cima Dome area. "A" is summit of Cima Dome.

Fig. 3. Colored lines represent the channel pattern as determined by waterbots as they move downslope. "A" is summit of Cima Dome. The channels are colored by magnitude of discharge (or contributing area). Blue represents a small discharge, with greens, yellows and reds representing higher discharges. The high discharge channels correspond to mapped ("blue line") channels found on the USGS 7.5 minute topographic quadrangles. Channels are dynamic, and small channels especially can change with time as sedimentation causes avulsion. This figure corresponds to flow from uniform rainfall over the entire area, but localized precipitation can also be modeled, leading to localized (asynchronous) flow in a subset of available channels, see Fig. 5.

Fig. 4. Erosion and deposition patterns in the Cima Dome area, Mojave Desert, California. Topography for maps here and below (except for Fig. 5) is from USGS 1/24,000 or 1/250,000 (Fig. 4) DEM data. Spot marked "A" corresponds to local topographic high (Cima Dome), and is marked on the maps shown in figures below as well. Waterbots dropped on each 30m X 30m pixel move downhill, entraining and detraining sediment according to changes in local slope. The erosion/deposition pattern calculated here matches approximately that seen in the field. Pink shading on insert shows area of near-surface bedrock, which approximately reflects region of net long-term erosion.

Fig. 5. Same as Fig. 3, except a localized flow has been initiated by precipitation near the area marked "A". This map is derived from USGS 1/250,000 quadrangles.

Fig. 6. Distribution of slope in the same area and at the same scale as that shown in Fig. 1. Lighter colors correspond to higher slopes. Deposition occurs where high gradients change to lower gradients along the path followed by individual waterbots. In the present version of the waterbot model, slope is the main controlling variable on waterbot dynamics and sediment capacity. However, the influence of changes in infiltration rate, exposure of bedrock, and similar features that can affect sediment transport can be included in the model in a straightforward way where field data is available.

Fig. 7: Schematic picture of waterbot model, in which discrete "water particles" move downslope, picking up and depositing sediment in accordance with a chosen sediment transport rule. Generally, as the slope steepens, waterbots tend

to pick up more sediment, and as slope flattens, they tend to drop some of the sediment they are carrying.

Fig. 8. Topographic map of a simulated uniformly sloping surface (downslope is to the left) upon which sits a nonerodible feature. The surface has been subject to erosion and deposition under the influence of a uniform rainfall. In nature, this feature might be a lava flow, or it might represent a man-made feature constructed, for example, of concrete. The deflection of contour lines in the vicinity of the obstacle indicates the growth of an upslope sediment stagnation zone, and an increase in downslope erosion. The region of orange coloration indicates the area from which upslope flows are deflected. Both of these effects are observable in the field. This example suggests schematically some ways in which the waterbot model might be applied.

Fig. 9: Man-made obstruction to flow – a freeway flood control berm is a construct in which a berm is created out of alluvial fan material that is typically bulldozed up from the fan surface, leaving a channel or ditch just upslope of the berm. Water running downslope is deflected into the berm. Lessening of the flow angle by deflection leads to enhanced sedimentation in the ditch.

Fig. 10: Schematic illustration of flow and enhanced sedimentation for a simulated berm similar to that in Fig. 9. Deposition upstream of the berm is accompanied by incision of upslope channels due to increased slope as the channels attempt to grade themselves to the bottom of the ditch. Enhanced erosion, on the other hand, is expected whenever a relatively unerodible surface sheds water discharge onto a more erodible surface, as shown in Fig. 8.

Fig. 11: Photograph of erosion features in lava flows in the Cima Dome area. Lack of sediment loading of water discharge running off the downstream end of the flows leads to enhanced incision into the pediment, and ultimately to gully (canyon) cutting into the lava itself. Similar erosion processes are expected to occur downslope of artificially constructed non-erodible surfaces.

Fig. 12: Gullies on artificial embankment could be modeled with standard sediment transport algorithms, but see Fig. 13.

Fig. 13: Characteristics of naturally occurring gullies in alluvial material (below the survey tripod) could not be matched by standard power-law sediment transport algorithms, indicating that these sediment transport rules may not always be adequate to explain details of erosion patterns.

Fig. 14: (a) Schematic flow diagram of program WATERBOT; (b) flow diagram indicating mapping of topographic information.

List of Publications and Abstracts

The following work was supported wholly or in part by ARO Grant Nos. : 30685-EV and 34207-EV-AAS:

Constitutive Laws and Prediction in Granular Systems

P. K. Haff

Proc. 10th Engineering Mechanics Conference, ASCE, Boulder, CO, S. Sture, ed., vol. 2, pp. 786-789 (1995).

Vertical Mixing of Grains During Bedload Transport

P. K. Haff

Proc. 10th Engineering Mechanics Conference, ASCE, Boulder, CO, S. Sture, ed., vol. 2, pp. 931-933 (1995).

Transport of Solids by Flowing Surface Water: Constitutive Rules for Simulation of Large-Scale Erosion of Sediments

J. Raghuraman and P. K. Haff

Proc. 32nd Annual Technical Meeting, Soc. Engineering Science, New Orleans, ed. D. Hui and S. Michaelides, pp 205-206, 1995.

Test of Scale Invariance of Hydrological Constitutive Laws

Allen G. Hunt

American Geophysical Union Abstracts, Fall Meeting, 1995, p. F182.

Clast Diffusion and Storm History of Desert Pavement

P. K. Haff

American Geophysical Union Abstracts, Fall Meeting, 1995, p. F270.

Gully-Head Dynamics on Desert Pavement, Mojave Desert

P. K. Haff

California, 1st Congress on Sedimentary Geology, Congress Program and Abstracts, vol. 1, p. 62, 1995.

Overturned Stones, Vegetation, and Stability of Desert Pavement Surfaces

P. K. Haff

26th Binghamton Geomorphology Symposium, Charlottesville, VA, Biogeomorphology: Terrestrial and Freshwater Aquatic Systems, Program and Abstracts, p. 27, 1995.

Limitations on Predictive Modeling in Geomorphology

P. K. Haff

in The Scientific Nature of Geomorphology, C. E. Thorn and B. Rhoads, eds., John Wiley pp. 337-358, John Wiley (1996).

Dynamical Processes on Desert Pavement and the Healing of Surficial Disturbances

P. K. Haff and B. T. Werner
Quaternary Research, 45, 38-46 (1996).

Microtopography as an Indicator of Modern Hillslope Diffusivity in Arid Terrain

R. Jyotsna and P. K. Haff
Geology, 25, 695-698 (1997)

Why Prediction of Grain Behavior is Difficult in Geological Granular Systems

P. K. Haff
Powders and Grains 97, Proc. of 3rd Intl. Conf. on Powders and Grains, Durham, NC, ed. R. P. Behringer and J. T. Jenkins, pp 61-64, Balkema, Rotterdam 1997

The Relation of Surface Characteristics to Landscape Evolution Processes in Arid Terrain

P. K. Haff
Eos Trans. AGU, Spring Meet. Suppl., 1997

Landscape Evolution Using Digital Elevation Models of the Cima Dome Area, Mojave Desert, California

L. R. Boring and P. K. Haff
Eos Trans. AGU, Fall Meet., 78, Suppl., pp F288-F289, 1997

An Empirical Model of Large Scale Sediment Transport in Arid Terrain: Application to Basalt Flow Erosion and Pediment Evolution near the Cima Volcanic Field, Mojave Desert, California

L. R. Boring and P. K. Haff, Geological Society of America Abstracts with Programs, 30, pp. A-360, 1998

Sediment Dynamics of Canyons and Fans of the Black Mountains, Death Valley, California.

P. K. Haff
Eos Trans. AGU, Fall Meet., vol. 79, Suppl., pp F306, 1998.

In preparation:

Climatic Dependence of Soil Erosion on a Small Hill in the Mojave Desert.
A. G. Hunt and Q. Joan Wu

A Probabilistic Treatment of Fluvial Entrainment of Cohesionless Particles.
A. G. Hunt

Models of Erosion and Deposition on Cima Dome, California
L. R. Boring

Invited Talks

"Localized Energy Dissipation in Strained Granular Material", 1st North American Workshop on Modeling the Mechanics of Off-Road Mobility, at US Army Engineer Waterways Experiment Station, Vicksburg, MS, 1995.

"Problems of Prediction in Natural Systems", 2nd North American Workshop on Modeling the Mechanics of Off-Road Mobility, at US Army Engineer Waterways Experiment Station, Vicksburg, MS, 1995.

"Desert Storms and Desert Pavement", at Duke University Quaternary Seminar, 1995

"Limitation on Predictive Modeling in Geomorphology", at 27th Binghamton Symposium in Geomorphology, Urbana, IL, 1996.

"Scaling-up of Small-Scale Sediment Transport Laws", at 11th Engineering Mechanics Conference, Fort Lauderdale, FL, 1996.

"Why Prediction of Grain Behavior is Difficult in Geological Granular Systems" at Intl. Conf. on Powders and Grains, Durham, NC., 1997.

"Surface Processes, Landscape Constitutive Relations and Human Disturbance of Arid Terrain", at US Army Construction Engineering Research Laboratory, Urbana, IL, 1997.

"Terrain Models with Potential Application to Landscape Features and Army Missions", at US Army Yuma Proving Ground Workshop, 1998.

"A PC-Based Model of Sediment Transport in Arid Terrain: Application to Erosion/Deposition Systems near Zzyzx, CA", at workshop on New Research Directions in Desert Surficial Processes and Landscape Dynamics on Military Lands, Zzyzx, CA, 1998.

Scientific Personnel Supported During Grant Period

P. K. Haff, Principal Investigator (30685-EV)

Allen G. Hunt, Graduate Student (34207-EV-AAS)

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Jyotsna Raghuraman. Postdoctoral Fellow (30685-EV)

Degrees Awarded

Allen G. Hunt

MS degree

Thesis title: Surface Transport Processes on a Small Hill in an Arid Environment
in Greenwater Valley, California (1996, unpublished).

Lonny R. Boring

MS Degree to be awarded may 1999



Figure 1

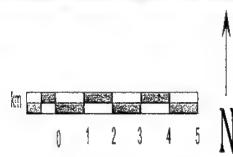
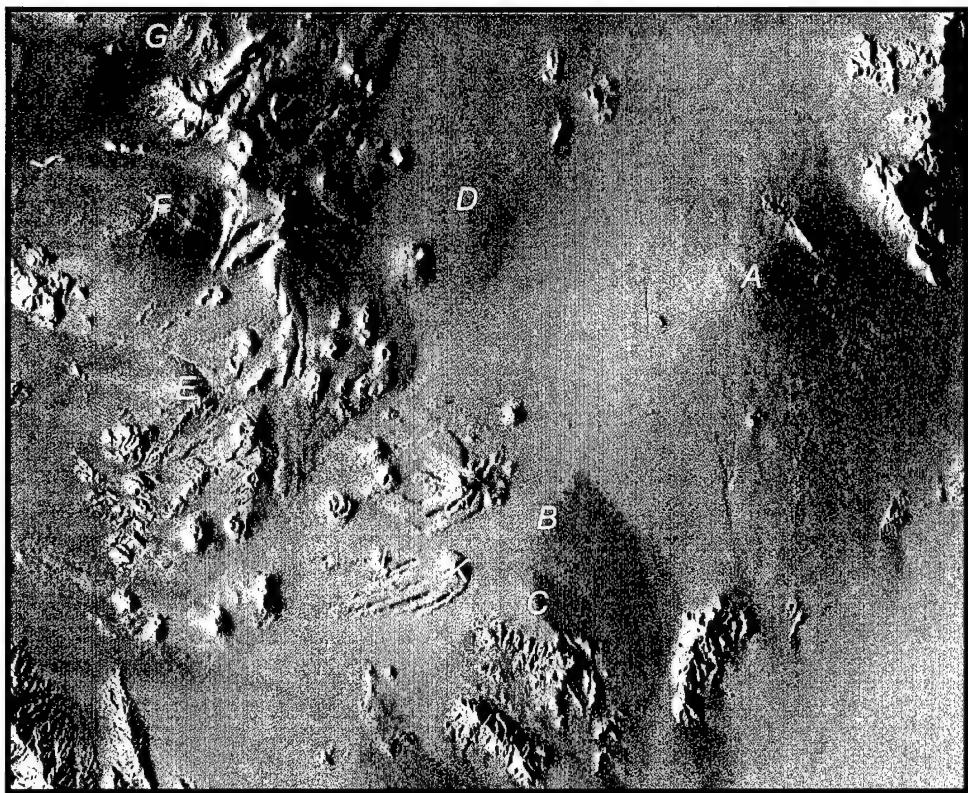


Figure 2

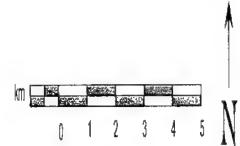
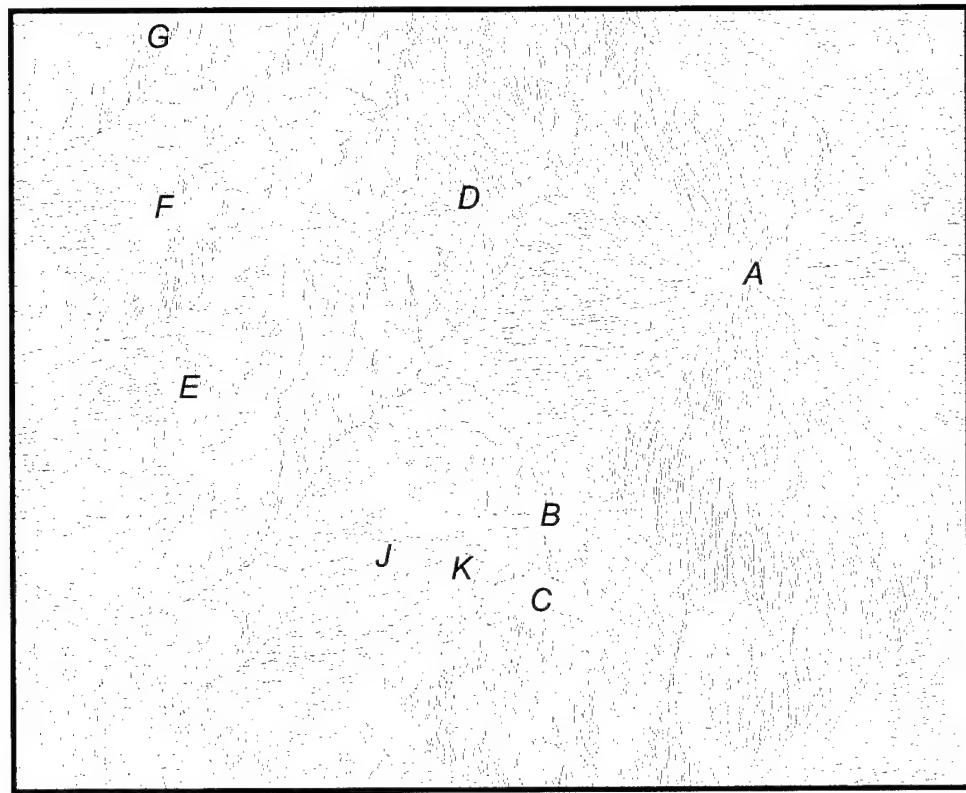


Figure 3

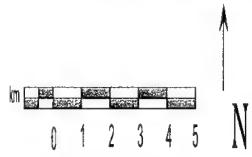
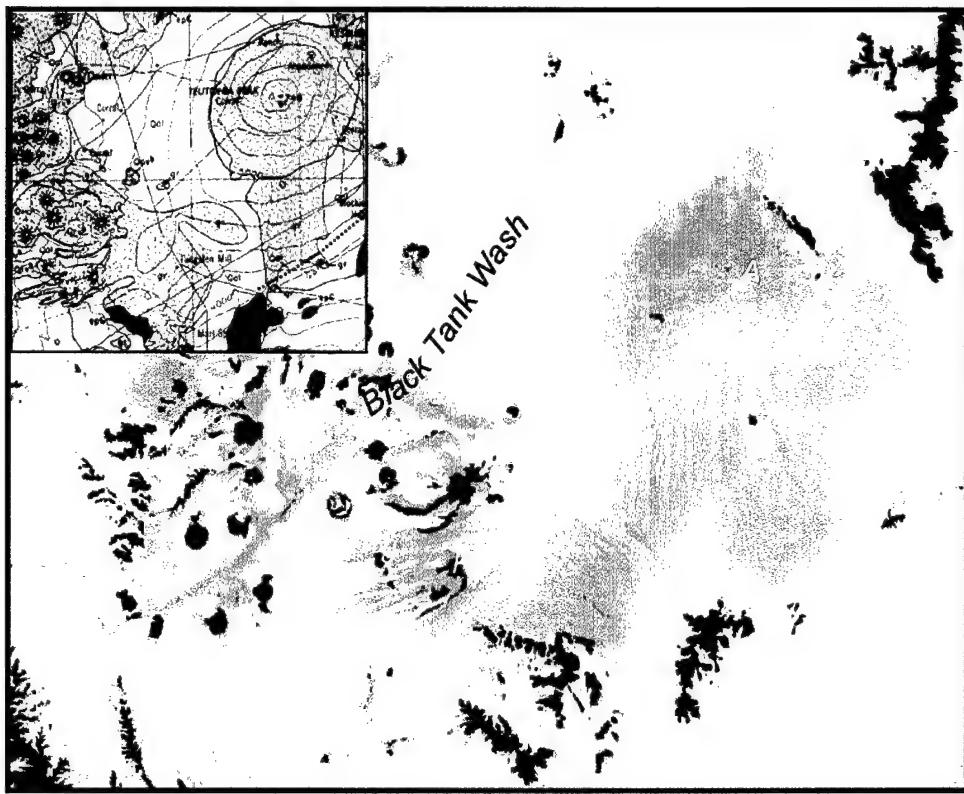


Figure 4



Figure 5 N

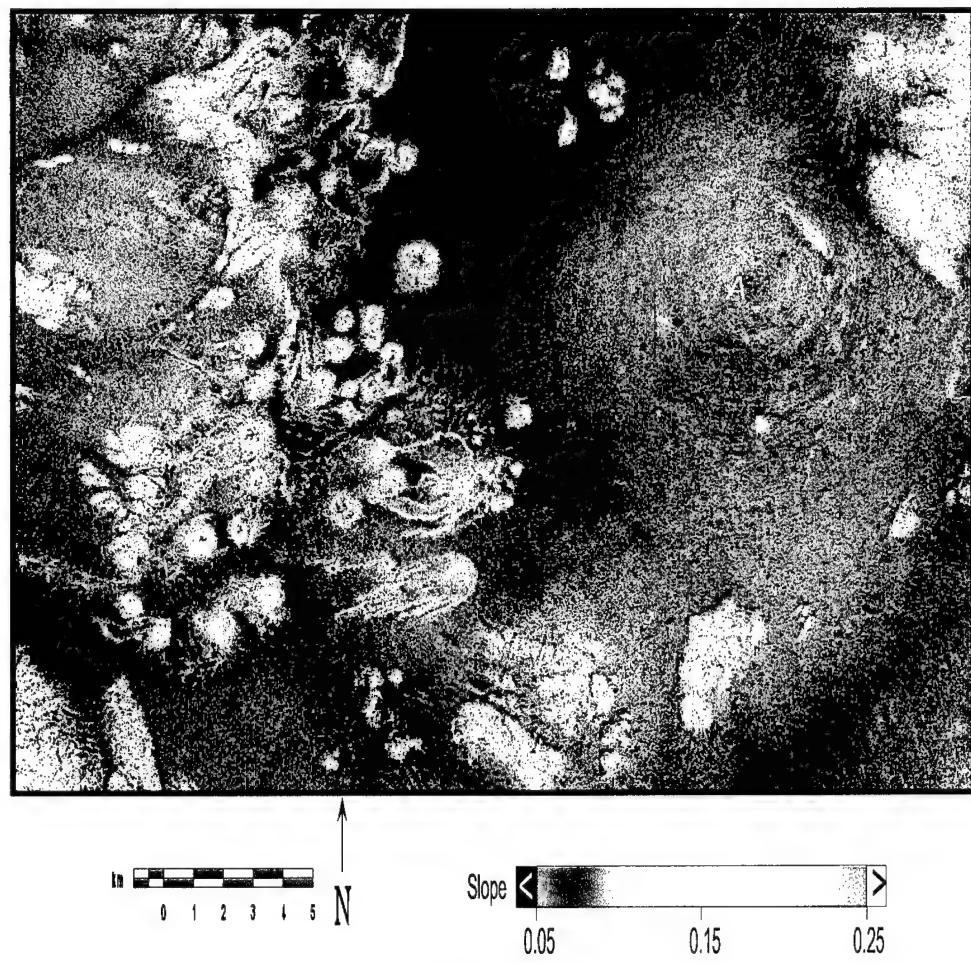


Figure 6.

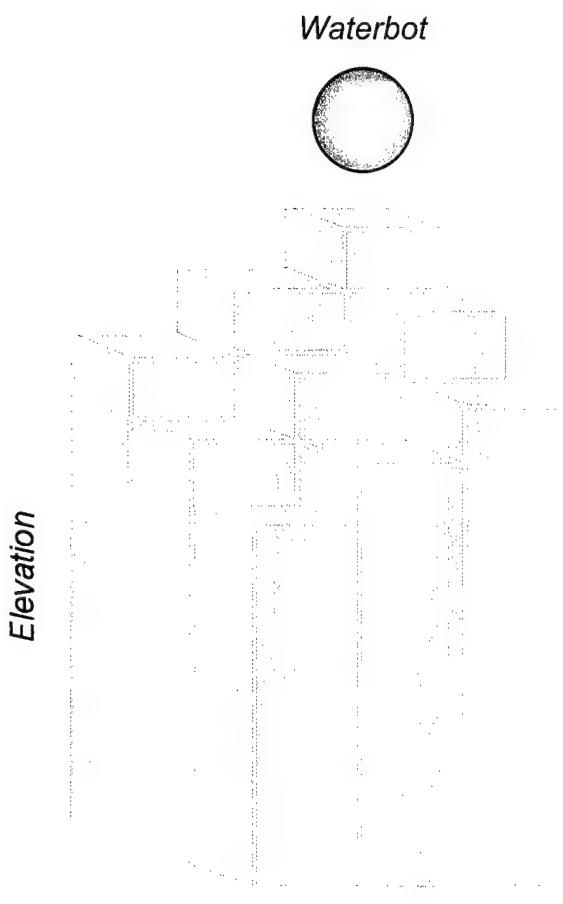
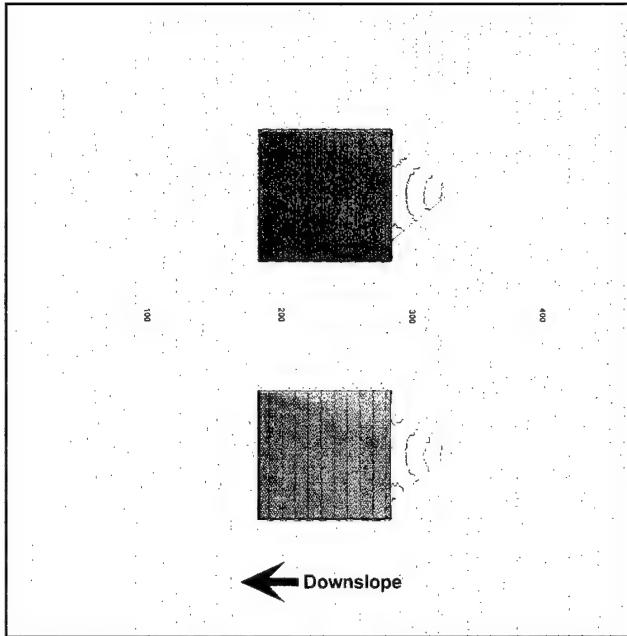


Figure 7.



km

0 1 2

Contour Interval = 10 m

Figure 8



Figure 9

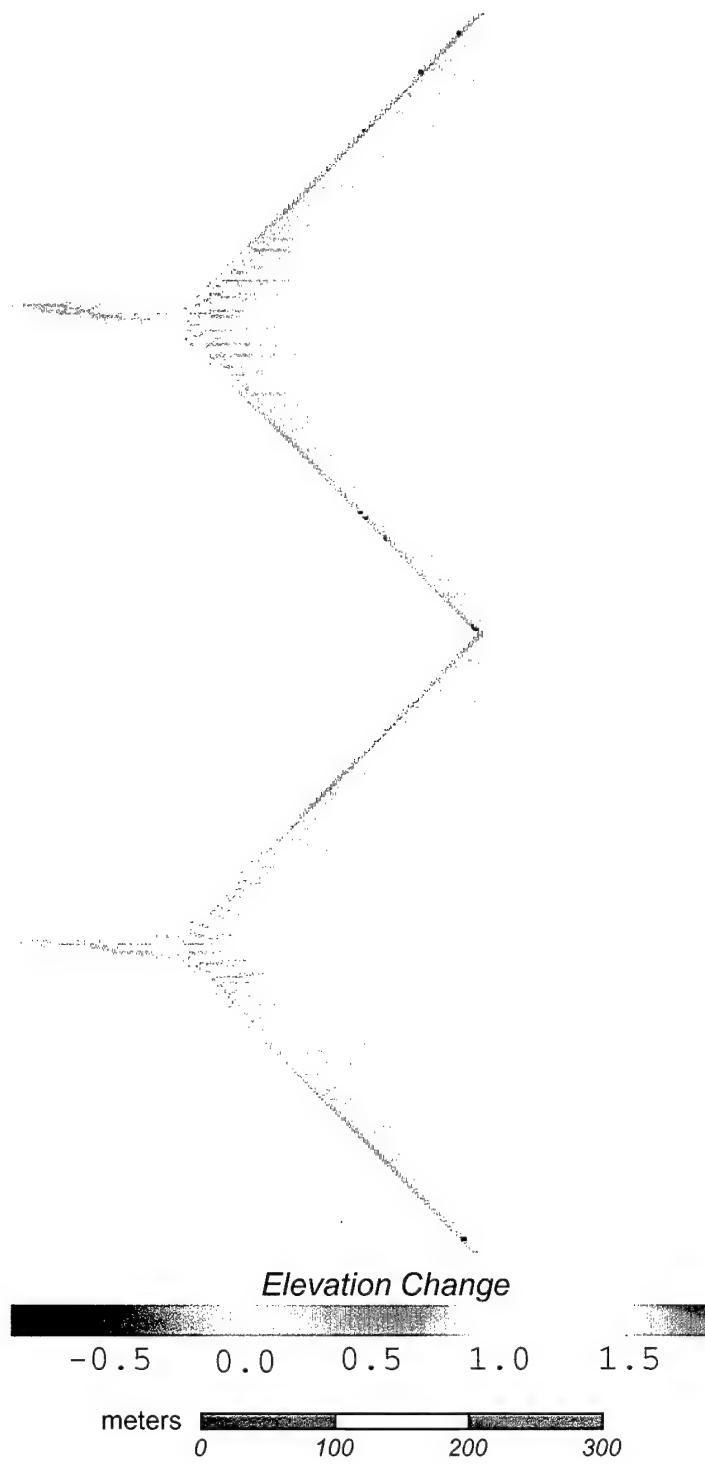


Figure 10

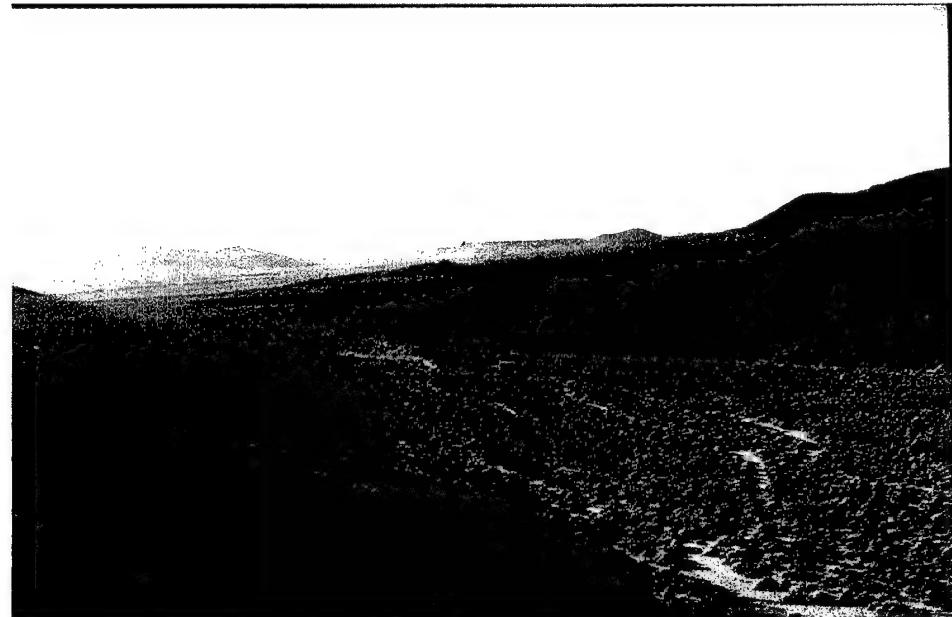


Figure 11

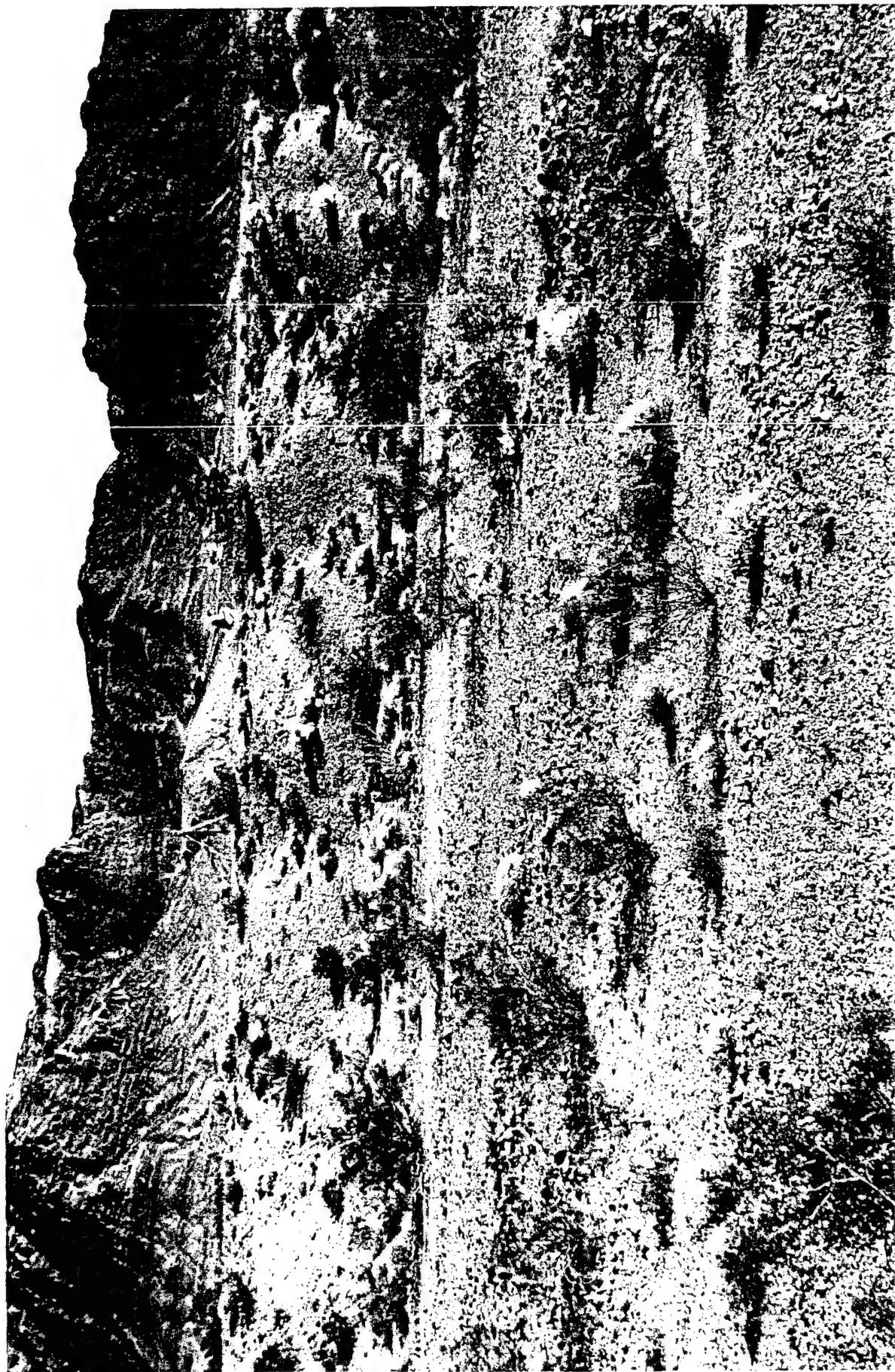


Figure 12

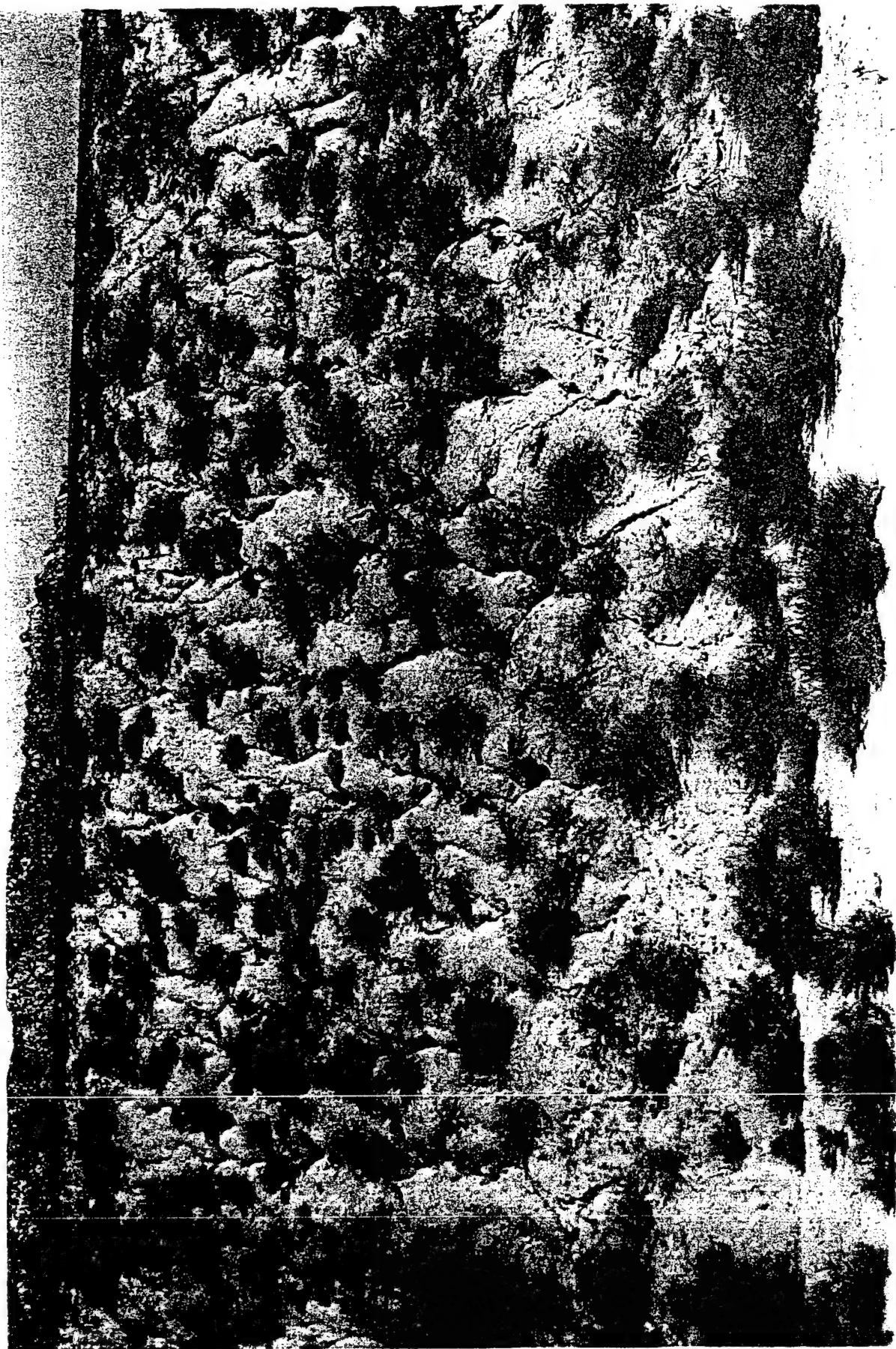


Figure 13

WATERBOT Model Flow Chart

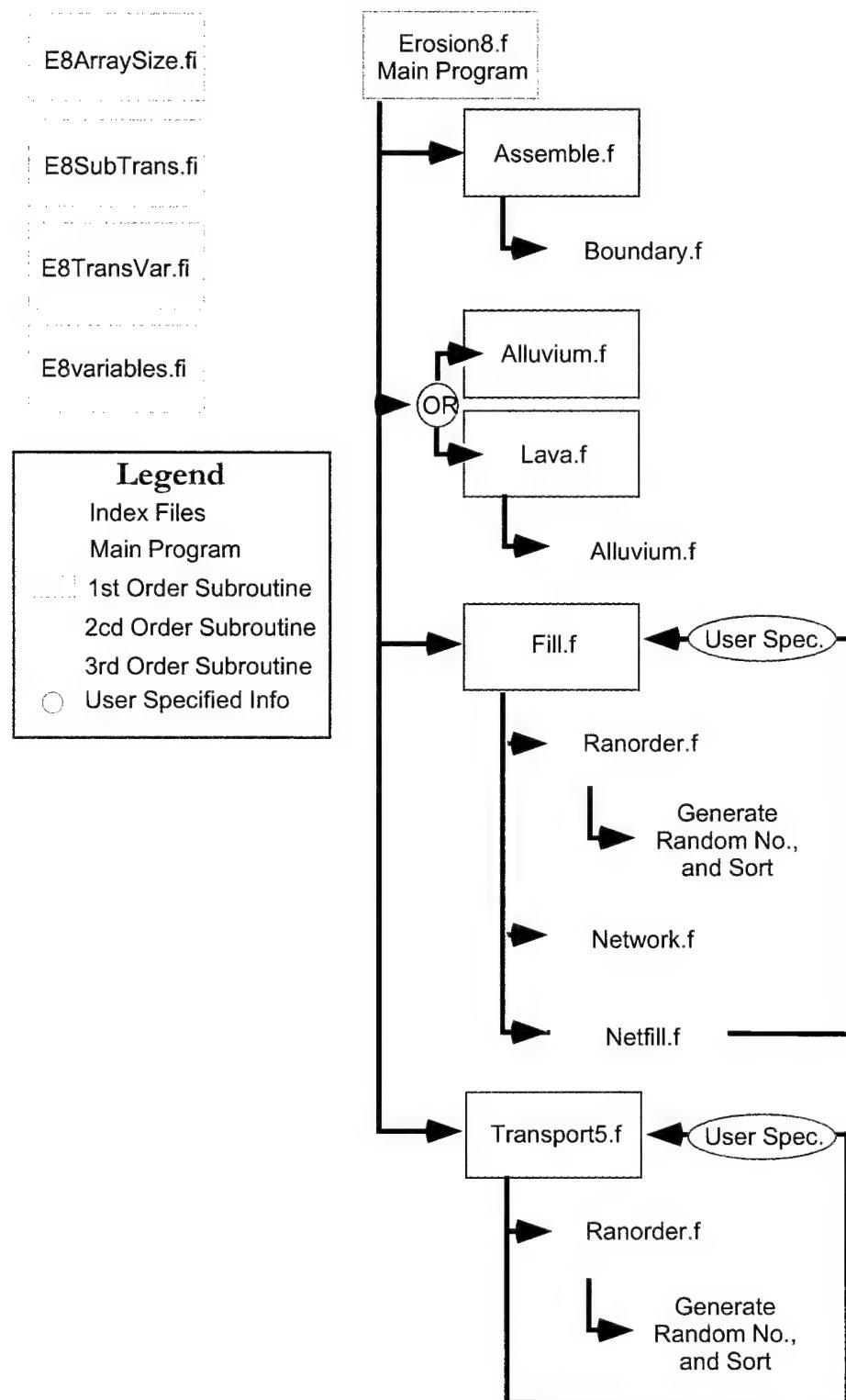


Figure 14a

WATERBOT Model Flow Chart

Mapping of Topographic Information

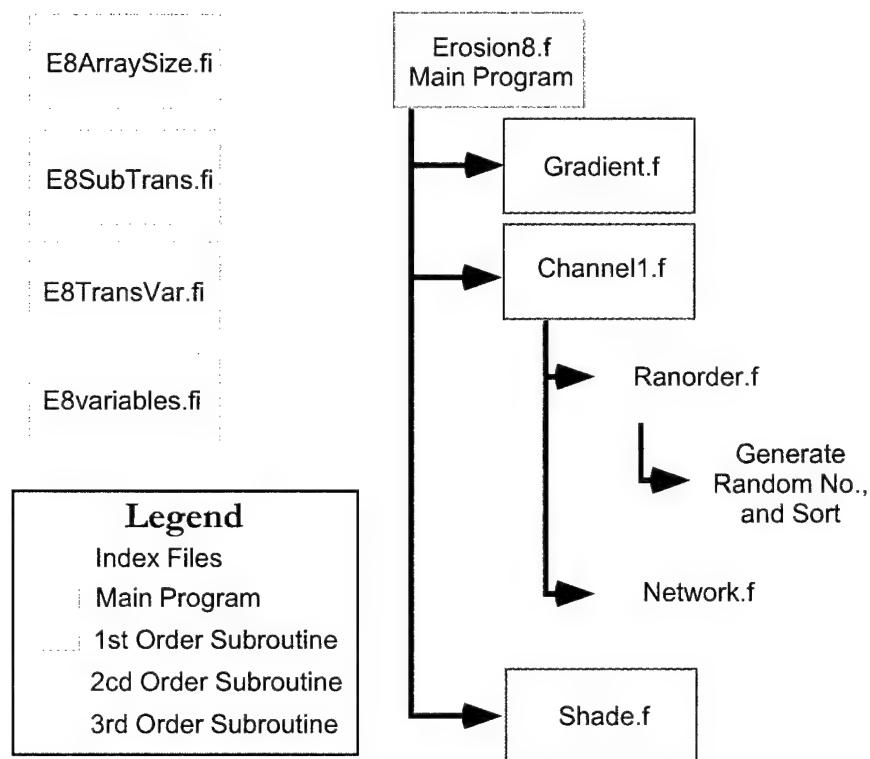


Figure 14b

Appendix: FORTRAN program WATERBOT

PROGRAM EROSION8

*\$noex

implicit none

- c Declaration of world variables
include 'E8variables.fi'
- c Assemble the native formate DEMs
call assemble(Z,space,south,north,west,east)
call alluvium(Z,cover,geology,south,north,west,east)
- c Read geology TIF file to delineate areas of basalt
! call lava(Z,cover,geology,basalthk,basaltbot,
! > south,north,west,east)
- c Fill pits in DEM data
call fill(Z,step1,step2,stream,south,north,west,east,
> Wro,Wco)
- c Map change in gradient
! call gradient(Z,DelG,south,north,west,east)
- c Call Sediment Transport subroutine
call transport5(Z,cover,modify,geology,basalthk,basaltbot,
> step1,step2,stream,n,south,north,west,east,Wro,Wco,counter2)
- c Delineate stream channels
! call channel1(Z,stream,counter1,step1,step2,n,south,north,
! > west,east,Wro,Wco)
- c Call subroutine to generate shaded relief map
! call shade(Z,shadow,space,south,north,west,east)

end PROGRAM EROSION8

```

subroutine assemble(Z,space,south,north,west,east)

*$noex
implicit none

c      Declaration of variables
include 'E8ArraySize.fi'
integer :: I          !Row index
integer :: J          !Column index
integer :: M          !Index to real in all elevation inputs
integer :: N          !Indes to read in each input file
integer :: unit1      !Number of lines for DEM south-to-north array
integer :: unit2      !Column number of DEM
integer :: unit3      !
integer :: number     !Number of elevation in south-to-north array
integer :: numfiles   !Number of input DEMs to assemble
integer :: Rows, Columns    !
integer :: Xposition, Yposition
integer :: K
integer :: G
integer :: south, north, west, east      !Values of map boundaries
integer :: flag        !Flag to write output files
integer :: Seed        !Random seed variable for random number

real :: Xcoor          !UTM X coordinate
real :: Ycoor          !UTM Y coordinate
real :: Xdatum          !Value to transform UTM to working array
real :: Ydatum          !Value to transform UTM to working array
real :: Xmax, Ymax     !Value to transform UTM to working array
real :: Ymaxtest
real :: sealevel
real :: minelev
real :: maxelev
real :: ran2
real :: random

real, dimension(MaxR,MaxC) :: Z      !Elevation array for study area
real, dimension(MaxR)       :: elev   !Holds elevation data
real :: space               !Horizontal resolution of USGS DEMs (m)

parameter (numfiles = 6)

call system_clock( Seed )

c      Input file names and units
open (unit=1, file='C:\MSDEV\Projects\Inputs\S_DEM.txt',
>      status='unknown')

```

```

open (unit=2, file='C:\MSDEV\Projects\Inputs\MM_DEM.txt',
>      status='unknown')
open (unit=3, file='C:\MSDEV\Projects\Inputs\C_DEM.txt',
>      status='unknown')
open (unit=4, file='C:\MSDEV\Projects\Inputs\GS_DEM.txt',
>      status='unknown')
open (unit=5, file='C:\MSDEV\Projects\Inputs\CC_DEM.txt',
>      status='unknown')
open (unit=6, file='C:\MSDEV\Projects\Inputs\CD_DEM.txt',
>      status='unknown')
open (unit=1, file='C:\MSDEV\Projects\Inputs\BB_DEM.txt',
>      status='unknown')
open (unit=1, file='C:\MSDEV\Projects\Inputs\HC_DEM.txt',
>      status='unknown')
open (unit=1, file='C:\MSDEV\Projects\Inputs\GP_DEM.txt',
>      status='unknown')
open (unit=2, file='C:\MSDEV\Projects\Inputs\IM_DEM.txt',
>      status='unknown')
open (unit=1,
>      file='C:\MSDEV\Projects\Inputs\Bill_DEMs\pintowells_CA.txt',
>      status='unknown')
open (unit=1,
>      file='C:\MSDEV\Projects\Inputs\Bill_DEMs\summerford_NM.txt',
>      status='unknown')

```

write (*,*) 'Assembling Information...'

```

Xdatum = 100000000.0
Ydatum = 100000000.0
Xmax = 0.0
Ymax = 0.0

```

c Scan data set to determine UTM location
do N = 1, numfiles
do M = 1, 500

```

read(N, *, end = 10) unit1,unit2,number,unit3,Xcoor,Ycoor

if (Xcoor .LE. Xdatum) then
    Xdatum = Xcoor
endif

if (Xcoor .GE. Xmax) then
    Xmax = Xcoor
endif

```

```

        if (Ycoor .LE. Ydatum) then
            Ydatum = Ycoor
        endif

        Ymaxtest = Ycoor + (float(number)-1.0)*space
        if (Ymaxtest .GE. Ymax) then
            Ymax = Ymaxtest
        endif

    enddo

10   continue
rewind N
enddo

c   Determine number of array rows and columns
Columns = INT(Xmax-Xdatum)/space
Rows = INT(Ymax-Ydatum)/space

c   Establish working array of elevation data
do N = 1, numfiles
    do M = 1, Columns

        >           read(N, *, end = 20) unit1,unit2,number,unit3,Xcoor,
                    Ycoor,sealevel,minelev,maxelev,(elev(K), K=1, number)

                    Xposition = INT((Xcoor-Xdatum)/space) + 1
                    Yposition = INT((Ycoor-Ydatum)/space) + 1

                    do G = 1, number
                        random = ran2( Seed )*0.5 - 0.25
                        Z(Yposition,Xposition) = elev(G) + random

                        >           if (Yposition .EQ. 252 .and. Xposition .GE. 469
                                    .and. Xposition .LE. 471) then
                            if (Xposition .EQ. 469) then
                                Z(Yposition,Xposition) = 1201.25
                            else if (Xposition .EQ. 470) then
                                Z(Yposition,Xposition) = 1201.40
                            else
                                Z(Yposition,Xposition) = 1201.50
                            endif
                        endif

                        Yposition = Yposition + 1

        enddo

```

```

        enddo
20 continue
    rewind N
    enddo

c      The follow extracts workable section for Cima Volcanic Field
!
!      south = 120
!      north = 350
!      west = 10
!      east = 620

c      Subroutine finds south, north, west, east values of working array
!
!      call boundary(Z,Rows,Columns,south,north,west,east)

      print*, 'Write OriginalZ.out and ERMapper.out Elevation files?'
      print*, '1 == Yes, 0 == No'
      read*, flag

      if (flag == 1) then
c          Output file names and units
          open (unit=30, file='OriginalZ.out', status='unknown')
          open (unit=50, file='ERMapperZ.out', status='unknown')

c          Write working array of elevation data to file.out
          do I = north, south, -1
              write(30,40) (Z(I,J), J = west, east)
          enddo

c          write XYX ASCII file for import into ERMapper
          do I = south, north
              do J = west, east
                  write(50,60) float(J*30), float(I*30), Z(I,J)
              enddo
          enddo

c          Close output files
          close (unit=30)
          close (unit=50)

      endif

c      Format statements
40 format (1X, 5000E15.8E2)
60 format (1X, 5000F12.4)
80 format (1X, 2E15.8E2, 1F12.4)

c      Close files

```

```
do l = 1, numfiles
    close (unit=l)
enddo

c      ending the subroutine
      return
end
```

```

subroutine boundary(Z,Rows,Columns,south,north,west,east)

*$noex
implicit none

include 'E8ArraySize.fi'

c      Declaration of variables
integer l, south, north, west, east, Rows, Columns, No, Ea
real Z
dimension Z(MaxR,MaxC)

c      Find working boundaries to elevation matrix
do l = 1, 15
    if (Z(l,Columns) .LT. 1.0) then
        south = south + 1
    endif
    if (Z(1,l) .LT. 1.0) then
        west = west + 1
    endif
    if (Z(Rows-l,1) .LT. 1.0) then
        No = No + 1
    endif
    if (Z(Rows,Columns-l) .LT. 1.0) then
        Ea = Ea + 1
    endif
enddo

south = south + 1
north = Rows - (No+1)
west = west + 1
east = Columns - (Ea+1)

return
end

```

```

subroutine alluvium(Z,cover,geology,south,north,west,east)

*$noex
implicit none
c      Declaration of variables
include 'E8ArraySize.fi'

integer :: south, north, west, east      !Location of map boundaries
integer :: I, J                          !Row (I) and Column (J) indices
real, dimension(MaxR,MaxC) :: Z          !Elevation array
real, dimension(MaxR,MaxC) :: cover       !Array of thickness of alluvial
cover
integer, dimension(MaxR,MaxC):: geology    !Array of geology type
real :: dep                                !Depth of alluvial cover

write (*,*) 'Initializing Alluvial Cover...'

c      Initialize cover to depth "dep"
do I = south, north
      do J = west, east

            dep = Z(I,J)
            cover(I,J) = dep
            geology(I,J) = 0

      enddo
enddo

return
end

```

```

subroutine lava(Z,cover,geology,basalthk,basaltbot,
>      south,north,west,east)

*noex
implicit none

c     Declaration of variables
include 'E8ArraySize.fi'

integer :: south, north, west, east      !Integer corners of Study area
integer :: I, J                          !Row (I) and Column (J) indices
integer, dimension(MaxR,MaxC):: geology

real, dimension(MaxR,MaxC)           :: Z
real, dimension(MaxR,MaxC)           :: cover
real, dimension(MaxR,MaxC)           :: basalthk
real, dimension(MaxR,MaxC)           :: basaltbot
real, parameter                      :: thickness = 3.0

c     Open Geology TXT file
open(unit=10, file='C:\MSDEV\Projects\Inputs\CVFGeology.txt',
>      status='old')

c     Initialize cover depth
call alluvium(Z,cover,geology,south,north,west,east)

write (*,*) 'Placing Lava Flows/Resistant Bedrock...'

do I = north, south, -1

    read(10, *, end=100) (geology(I,J), J = west, east)

enddo
100 continue

do I = south, north
    do J = west, east

        if (geology(I,J) .EQ. 176) then !Read GEOLOGY from TIFF
            basalthk(I,J) = thickness
            basaltbot(I,J) = Z(I,J) - thickness
            geology(I,J) = 1
            cover(I,J) = 0.0
        else
            geology(I,J) = 0
        endif

    !         geology(I,J) = 0          !Make all material PEDIMENT Type
    enddo
enddo

```

```
        enddo
      enddo

c     Write output of DelG to output file
      open(unit=10, file='Geology.out', status='unknown')
      open(unit=30, file='BasThk.out', status='unknown')
      open(unit=50, file='BasBot.out', status='unknown')
      open(unit=70, file='Cover.out', status='unknown')

      do I = north, south, -1
        write(10,20) (geology(I,J), J = west, east)
        write(30,40) (basalthk(I,J), J = west, east)
        write(50,40) (basaltbot(I,J), J = west, east)
        write(70,40) (cover(I,J), J = west, east)
      enddo

      do I = 10, 70, 10
        close (unit=I)
      enddo

20    format (1X, 5000I12)
40    format (1X, 5000E15.8E2)

      return
    end
```

```

subroutine fill(Z,step1,step2,stream,south,north,west,east,
>      Wro,Wco)

*$noex
implicit none

c     Declaration of variables
include 'E8ArraySize.fi'

real :: modify(MaxR,MaxC) !2D array of amount of elevation change (+/-)

!MODIFY is calculated/updated in the TRANSPORT subroutines
integer :: stream(NumCells,3) !Contains (Column,Row,Integer Location
                             !of next step position)

!STREAM is created in the RANORDER subroutine
integer :: depress(NumCells,3) !Contains (Column,Row,Integer Location
                               !of next step position)
integer :: step2(NumCells)    !Contains integer position (Translatable
                             !to Row,Column)
integer :: south, north, west, east      !Location of map boundaries
integer :: Wro                      !Number of working Rows
integer :: Wco                      !Created in RANORDER
integer :: n                         !Number of working Columns
integer :: A, B, F, S                !Created in RANORDER
integer :: X, Y                      !Number of topographic cells
integer :: count                     !array indices
                                      !Position in map
                                      !(Row == Y, Column == X)
                                      !Counter index to assign values
                                      !within Depress array

c     Array indices
integer :: I                         !Row index
integer :: J                         !Column index

real, dimension(MaxR,MaxC) :: Z      !Elevation matrix
real :: diffelev                    !Difference in Elev of current cell
                                      !and neighbor
real :: mindiff                     !Holds value of Minimum
                                      !difference in elevation
real :: step1(NumCells)             !Random numbers to sort and
                                      !generate random waterbot drop

n = Wro*Wco

c     Call subroutine spatial to generate 1D array of elevations
c     Subroutine 'ranorder' is required for both Subroutines 'transport'
call ranorder(step1,step2,stream,n,south,north,west,east,Wro,Wco)

```

```

c      Call subroutine network to calculate and store position of
c      maximum gradient
call network(Z,stream,south,north,west,east,Wro,Wco)

do F = 1, 200

write (*,*) 'Filling Depressions...', F
count = 0

c      Scan all positions in stream looking for depressions
do S = 1, n

if (stream(S,3) .GT. n) then

    count = count + 1
    depress(count,3) = stream(S,3)
    depress(count,1) = stream(S,1)
    depress(count,2) = stream(S,2)
    X = stream(S,1)
    Y = stream(S,2)
    mindiff = 100.0

    do A = -1, 1
        do B = -1, 1

            diffelev = Z(Y+A,X+B) - Z(Y,X)
            if (diffelev .LT. mindiff .AND. diffelev .NE. 0.0)
                then
                    mindiff = diffelev
                else
                    endif

            enddo
        enddo

c      Increase depression elev to lowest contributing elev
        modify(Y,X) = modify(Y,X) + mindiff + 0.01
        Z(Y,X) = Z(Y,X) + mindiff + 0.01

        endif

    enddo

c      Re-establish the drainage network
    call netfill(Z,stream,depress,count,south,north,west,east,
>              Wro,Wco)

```

```
        enddo

c      Write output to output files
open(unit=30, file='FilledZ.out', status='unknown')
open(unit=50, file='FilMod.out', status='unknown')

      do I = north, south, -1
      *           write(50,400) (modify(I,J), J = west, east)
      *           write(30,400) (Z(I,J), J = west, east)
      enddo

      close (unit=30)
      close (unit=50)

400  format (1X, 5000E15.8E2)

      return
      end
```

```

subroutine ranorder(step1,step2,stream,n,south,north,west,east,
>      Wro,Wco)

*$noex
implicit none

c      Declaration of variables
include 'E8ArraySize.fi'

integer :: stream(NumCells,3)      !Contains (Column,Row,Integer Location
                                    !of next step position)

!STREAM is created in the RANORDER subroutine
integer :: step2(NumCells)        !Contains integer position
                                    !Translatable to Row,Column)
integer :: south, north, west, east      !Location of map boundaries
integer :: Wro                      !Number of working Rows in map.
integer :: Wco                      !Number of working Columns in map.
integer :: n                         !Number of topographic cells in map
integer :: Seed                     !Random seed for number generator
integer :: I,J                       !Row (I) and Column (J) indices
integer :: position                 !Counter index for position pointer in
                                    !Step arrays

real :: step1(NumCells)            !Random numbers to sort and generate
                                    !random waterbot drop
real :: ran3                      !Random number function (-ve input)
real :: jack                      !Random number b/t 0.0 and 1.0E06

write (*,*) 'Ordering Information...'

call system_clock( Seed )          !Call clock to generate Seed Variable
Seed = -Seed                      !Function ran3 uses (-ve) Seed

Wro = north-south+1
Wco = east-west+1
position = 0

do J = west, east
    do I = south, north

        position = position + 1

        jack = ran3( Seed )*1000000.0

        step1(position) = jack

```

```
step2(position) = position  
stream(position,1) = J  
stream(position,2) = I  
enddo  
enddo  
n = position  
c      Call sort2 to organize order of random particle drops  
call sort2(n,step1,step2)  
return  
end
```

```

subroutine network(Z,stream,south,north,west,east,
>      Wro,Wco)

*$noex
implicit none

c     Declaration of variables
include 'E8ArraySize.fi'

integer :: stream(NumCells,3) !Contains (Column,Row,Integer Location
                             !of next step position)

!STREAM is created in the RANORDER subroutine
integer :: south, north, west, east !Location of map boundaries
integer :: Wro                      !Number of working Rows in map.
integer :: Wco                      !Created in RANORDER
integer :: I,J                      !Number of working Columns in map.
integer :: position                 !Created in RANORDER
integer :: position                 !Row (I) and Column (J) indices
integer :: position                 !Counter index for position pointer in
                                   !step arrays

c     Position Indices
integer :: A           !Scan Row
integer :: B           !Scan Column
integer, parameter :: scan = 1 !Defines size of box to scan gradients
integer :: AmaxG       !Holds Scan Row of maximum gradient
integer :: BmaxG       !Holds Scan Column of maximum gradient

c     Togography variables, Directionality variables
real :: DeltaZ        !Elev. difference b/t current cell and neighbor
real, dimension(MaxR,MaxC) :: Z          !Elevation matrix
real :: max            !Holds value of maximum gradient (using RHO8)
real :: rho8           !Fairfields (1991) directionality variable
integer :: Seed         !Random seed variable for random number
real :: ran2            !Random number generator 2 (+ve input)
real :: random          !Random number b/t 0.0 and 1.0

c     Variables for file output
integer :: S
integer :: P
integer :: flag

write (*,*) 'Creating Network Information...'

call system_clock( Seed ) !Call clock to generate Seed Variable

c     Scan each elevation bin in working elevation matrix w/n edges
do I = south+1, north-1
    do J = west+1, east-1

```

```

        AmaxG = 0
        BmaxG = 0
        max = 0.0

c      Delineate stream network with Rho8
do A = -scan, scan, 1
    do B = - scan, scan, 1

c      Calculate grad for scan .EQ. 1
c      Cardinal directions
if ( (B .EQ. 0 .AND. (A .EQ. +scan .OR. A .EQ.
    -scan)) .OR. (A .EQ. 0 .AND. (B .EQ. -scan
    .OR. B .EQ. +scan))) then

        DeltaZ = (Z(I,J)-Z(I+A,J+B))
        DeltaZ = (Z(I,J)-Z(I+A,J+B))

c      Diagonal directions
else

        random = ran2(Seed)
        rho8 = 1.0 / (2.0-random)

        DeltaZ = rho8 * (Z(I,J)-Z(I+A,J+B))
        DeltaZ = (Z(I,J)-Z(I+A,J+B))

endif

c      Check for maximum DeltaZ
if(DeltaZ .GE. max) then
    max = DeltaZ

    AmaxG = A
    BmaxG = B
endif

c      End adjacent bin scanning do loops
enddo
enddo

c      Determine postion in step array from to I,J location
position = I-south + (J-west)*Wro + 1

```

```

c           Record the step location in network matrix

>         if (AmaxG .EQ. 0 .and. BmaxG .EQ. 0) then
            stream(position,3) = Wro*Wco+10
        else
            stream(position,3) = position + AmaxG +
            (BmaxG*(Wro))
        endif

c           End do loops to check each elevation bin
        enddo
    enddo

c           Put 0 also in edge bins
    do I = 1, Wro, 1
        stream(I,3) = 0
        stream(I,3) = 0
    enddo
    do I = (Wro*Wco), (Wro*Wco-Wro+1), -1
        stream(I,3) = 0
        stream(I,3) = 0
    enddo

    do J = 1, (Wro*Wco), Wro
        stream(J,3) = 0
        stream(J,3) = 0
    enddo
    do J = Wro, (Wro*Wco), Wro
        stream(J,3) = 0
        stream(J,3) = 0
    enddo

    print*, 'Write Stream.out output file?'
    print*, '1 == Yes, 0 == No'
    read*, flag

    if (flag == 1) then
        open(unit=10, file='Stream.out', status='unknown')
        do S = 1, (Wro*Wco)
            write(10,200) (stream(S,P), P = 1,3)

        enddo
        close(unit=10)
    endif

200 format(1X, 3I10)

```

```
return  
end
```

```

subroutine netfill(Z,stream,depress,count,south,north,west,east,
>                  Wro,Wco)

*$noex
implicit none

c      Declaration of variables
include 'E8ArraySize.f1'

integer :: stream(NumCells,3) !Contains (Column,Row,Integer Location
                             !of next step position)

!STREAM is created in the RANORDER subroutine
integer :: south, north, west, east !Location of map boundaries
integer :: Wro                      !Number of working Rows in map.
                                      !Created in RANORDER
integer :: Wco                      !Number of working Columns in map.
                                      !Created in RANORDER
integer :: I,J                      !Row (I) and Column (J) indices
integer :: position                 !Counter index for position pointer in step arrays
integer :: count                    !Number of depressions in map
integer :: N                        !Do loop index
integer :: depress(NumCells,3) !Array containing Column,Row,Location
                             !of depression

c      Position Indices
integer :: A                         !Scan Row
integer :: B                         !Scan Column
integer, parameter :: scan = 1 !Defines size of box to scan gradients
integer :: AmaxG                     !Holds Scan Row of maximum gradient
integer :: BmaxG                     !Holds Scan Column of maximum gradient
c      Togography variables, Directionality variables
real :: DeltaZ                      !Elev. difference b/t current cell and neighbor cells
real, dimension(MaxR,MaxC) :: Z       !Elevation matrix
real :: max                          !Holds value of maximum
                                      !gradient (using RHO8)
real :: rho8                         !Fairfields (1991) directionality variable
integer :: Seed                       !Random seed variable for random number
real :: ran2                         !Random number generator 2 (+ve input)
real :: random                       !Random number b/t 0.0 and 1.0

write (*,*) 'Reestablishing Network Information...',  

>           'Number of Depressions = ', count

call system_clock( Seed )           !Generate random seed variable for ran2

c      Scan each elevation bin in working elevation matrix w/n edges
do N = 1, count

```

```

do I = (depress(N,2)-scan), (depress(N,2)+scan)
do J = (depress(N,1)-scan), (depress(N,1)+scan)
    if (I .GT. south .and. I .LT. north .and.
        J .GT. west .and. J .LT. east) then

        AmaxG = 0
        BmaxG = 0
        max = 0.0

c      Delineate stream network with Rho8
        do A = -scan, scan, 1
            do B = - scan, scan, 1

c      Calculate grad for scan .EQ. 1
c      Cardinal directions
        if ( (B .EQ. 0 .AND. (A .EQ. +scan .OR. A .EQ.
            -scan)) .OR. (A .EQ. 0 .AND. (B .EQ. -scan
            .OR. B .EQ. +scan))) then

            DeltaZ = (Z(I,J)-Z(I+A,J+B))
            DeltaZ = (Z(I,J)-Z(I+A,J+B))/30.0

c      Diagonal directions

        else

            Random = ran2( Seed )
            rho8 = 1.0 / (2.0-random)

            DeltaZ = rho8 * (Z(I,J)-Z(I+A,J+B))
            DeltaZ = (Z(I,J)-Z(I+A,J+B))/(42.4264)

        endif

c      Check for maximum DeltaZ
        if(DeltaZ .GE. max) then
            max = DeltaZ

            AmaxG = A
            BmaxG = B
        endif

c      End adjacent bin scanning do loops
        enddo
    enddo

```

```

c      Determine position in step array from to I,J location
position = I-south + (J-west)*Wro + 1

c      Record the step location in network matrix

      if (AmaxG .EQ. 0 .and. BmaxG .EQ. 0) then
          stream(position,3) = Wro*Wco+10
      else
          stream(position,3) = position + AmaxG +
          (BmaxG*(Wro))
      endif

      endif

c      End do loops to check each elevation bin
      enddo
      enddo

      enddo

c      Put 0 also in edge bins
      do I = 1, Wro, 1
          stream(I,3) = 0
          stream(I,3) = 0
      enddo
      do I = (Wro*Wco), (Wro*Wco-Wro+1), -1
          stream(I,3) = 0
          stream(I,3) = 0
      enddo

      do J = 1, (Wro*Wco), Wro
          stream(J,3) = 0
          stream(J,3) = 0
      enddo
      do J = Wro, (Wro*Wco), Wro
          stream(J,3) = 0
          stream(J,3) = 0
      enddo

      return
end

```

```

subroutine transport5(Z,cover,modify,geology,basalthk,basaltbot,
>      step1,step2,stream,n,south,north,west,east,Wro,Wco,counter2)

*noex
implicit none

c      Declaration of variables
c      Defining common ARRAY dimensions
include 'E8ArraySize.fi'

c      Two-D ARRAYs (Matrix of Data)
real :: Z(MaxR,MaxC)    !2D array of elevation data
                           !Z is created in the ASSEMBLE subroutine
real :: cover(MaxR,MaxC)   !2D array of thickness of alluvial cover
                           !COVER is created in the ALLUVIUM
real :: modify(MaxR,MaxC)   !2D array of amount of elevation change

!MODIFY is calculated/updated in the TRANSPORT subroutines
integer :: counter2(MaxR,MaxC) !2D array containing number of
                               !WATERBOTS passing thru each cell

!COUNTER2 is calculated/updated in the TRANSPORT subroutines
integer :: geology(MaxR,MaxC) !GEOLOGY contains information on the
                               !type of material present in cell

!GEOLOGY is created in the LAVA subroutine
real :: basalthk(MaxR,MaxC)   !BASALTHK contains the thickness of
                               !the Basalt in the Cell

!BASALTHK is created in the LAVA subroutine
real :: basaltbot(MaxR,MaxC)   !BASALTBOT contains the elevation of
                               !the basalt bottom

!BASALTBOT is created in the LAVA subroutine
real :: BotCount(MaxR,MaxC)    !BOTCOUNT contains the Count of
                               !waterbot when basalt was breached

!BOTCOUNT is output to files after each iteration
character*16 :: filename(40,6)  !FILENAME holds the output file names

c      One-D ARRAYS
real :: step1(NumCells) !1D array of random numbers b/t 1, NumCells
                           !used to sort random waterbot drop sequence

!STEP1 is created in the RANORDER subroutine
integer :: step2(NumCells)   !1D array of unique integer location
                           !(translatable to Row,Column) of each
                           !elevation

```

!STEP2 is created in the RANORDER subroutine
integer :: stream(NumCells,3) !Contains (Column,Row,Integer Location
!of next step position)

!STREAM is created in the RANORDER subroutine

c DEM variables Size, Dimensions, Etc.
integer :: south !Value of Row (+ve from south) of Southern Boundary
integer :: north !Value of Row (+ve from south) of Northern Boundary
integer :: west !Value of Row (+ve from west) of Western Boundary
integer :: east !Value of Row (+ve from west) of Eastern Boundary
integer :: n !Number of elevation cells in the Z array

!Calculated in RANORDER subroutine
integer :: Wro !Number of Rows in working Z array, in RANORDER
integer :: Wco !Number of Columns in working Z array, in RANORDER
real :: space = 30.0 !Horizontal resolution of USGS DEMs (m)
integer :: count !Counts number of times Subroutine is called

real :: outH !Thickness of material leaving topo cell (-ve)
real :: fraction !Fraction of total material to erode that is
!contained w/n alluvium

real :: degree = 20.0*(0.01745) !Threshold slope to move basalt material
!(Degree*Radian Conversion)
real :: Bthreshk = 0.05 !Threshold thickness of basalt to treat as
!basalt material
real :: Bthresconcen = 250 !Threshold concentration to move basalt
!counter 2 counts waterbots previously
!moved thru current cell

c Declaration of local variables
include 'E8TransVar.fi'
include 'E8SubTrans.fi'

integer :: file !Index used to close output files

call system_clock(Seed) !Call clock for seed

c Initialize FILENAME array for output file names.
open(unit=150, file='FileName.txt', status='old')
open(unit=250, file='HeadChan.out', status='unknown')

do I = 1, INT(Totyears/Time)
 read(150,*) (filename(I,J), J = 1, 6)
 write(*,*) (filename(I,J), J = 1, 6)
enddo

```

close(unit=150)

c      Initialize position locations in DeltaZ array (Row,Column,(Elev. Diff))
C = 0
do B = -scan, scan, 1
    do A = -scan, scan, 1

        C = C + 1
        DeltaZ(C,1) = A
        DeltaZ(C,2) = B

    enddo
enddo

call ranorder(step1,step2,stream,n,south,north,west,east,
>           Wro,Wco)

c      DO LOOP to evolve landscape thru time
do T = 1, INT(Totyears/Time)

    write(*,*) 'Calculating Sediment Transport...', T, ' of',
>           INT(Totyears/Time)

    count = 0

c      Reset counter2 array to zero
do I = south, north
    do J = west, east

        counter2(I,J) = 0

    enddo
enddo

c      DO LOOP to hit each Row,Column position in Z array
do S = 1, n

    I = stream(step2(S),2) !Extract Row from STREAM array
    J = stream(step2(S),1) !Extract Column from STREAM array

    inH = 0.0                      !!Initialize inH to Zero
    Rolls = 0.0                     !!Initialize Rolls to Zero

c      DO LOOP to follow Waterbot position and calculate to boundary
    do while (I >= south+1 .AND. I <= north-1
>           .AND. J >= west+1 .AND. J <= east-1)

```

```

AmaxG = 0      !Initialize Row to ZERO
BmaxG = 0      !Initialize Column to ZERO
max = 0.0       !Initialize MaxGrad to ZERO
DeltaH = 0.0    !Initialize Elevation diff to ZERO
Rolls = Rolls + 1.0   !Increment the Rolls
C = 0          !Set DeltaZ array to ZERO
counter2(I,J) = counter2(I,J) + 1
                           !Increment COUNTER2 by one

c
Scan Eight Neighbors and locate maximum gradient
do B = -scan, scan, 1  !B to Columns
do A = -scan, scan, 1  !A to Rows

C = C + 1
!Cardinal Directions
if ((B==0.AND.(A==+scan.OR.
>           A== -scan)).OR. (A == 0 .AND.
>           (B == +scan .OR. B == -scan))) then
DeltaZ(C,3) = (Z(I,J)-Z(I+A,J+B))
Delta = DeltaZ(C,3)

!Corners
else

random = ran2( Seed )
!Generate random number
rho8 = 1.0/(2.0-random)
!Calculate RHO8

DeltaZ(C,3) = (Z(I,J)-Z(I+A,J+B))
Delta = rho8*DeltaZ(C,3)

endif

!Check for maximum gradient to
neighbors
if (Delta >= max) then
  max = Delta
  maxdelZ = DeltaZ(C,3)
  AmaxG = A
  BmaxG = B
endif

enddo !END A (Row) scan of
neighbors
enddo      !END B (Column) scan of
neighbors

```

```

if (AmaxG == 0 .AND. BmaxG == 0) then
!Waterbot is in a Hole

min = -100.0

do C = 1, 9
if (DeltaZ(C,3) > min .AND. C /= 5) then

    min = DeltaZ(C,3)
    AmaxG = DeltaZ(C,1)
    BmaxG = DeltaZ(C,2)
endif
enddo

min = min-0.0001

c
If sed. load is enough to fill depression
if (inH > -min) then
    DeltaH = -min
    cover(I,J) = cover(I,J) + DeltaH
    Z(I,J) = Z(I,J) + DeltaH
    modify(I,J)=modify(I,J) + DeltaH
    inH = inH - DeltaH
    I = I + AmaxG
    J = J + BmaxG
    counter2(I,J) = counter2(I,J) + 1
    goto 20
else
    If sed. load is not enough to fill depression
    else
        DeltaH = inH
        cover(I,J) = cover(I,J) + DeltaH
        Z(I,J) = Z(I,J) + DeltaH
        modify(I,J)=modify(I,J) + DeltaH
        counter2(I,J) = counter2(I,J) + 1
        goto 30
    endif
else
    !Waterbot is not in a Hole
    length = (SQRT((float(AmaxG))**2 +
    !Calculate distance next step
    (float(BmaxG))**2))*space
    grad = maxdelZ / length
    !Calculate gradient to next step
    grad = 0.0
endif
!
>
!
```

```

c           Find the desired change in cell height (outH)
!
outH = Const*Rate*Time*grad
if (Rolls < step) then
    outH=Const*Rate*Time*grad*(Rolls/step)
else
    outH = Const*Rate*Time*grad
endif

DeltaH = inH-outH

c           Adjust Z to Erode or Deposit difference between
c           outH and inH

c           If Alluvium is Greater Than Erosion amount
c           if (DeltaH < 0.0 .AND. (-DeltaH) <= cover(I,J))
c               then
c                   cover(I,J) = cover(I,J) + DeltaH

c           If Alluvium is Less Than (<) Erosion amount
c           else if (DeltaH < 0.0 .AND. (-DeltaH) >
c                   cover(I,J)) then
c                       fraction = cover(I,J) / DeltaH

c           if (geology(I,J) == 1 .AND. (grad >=
c               TAN(degree).OR. counter2(I,J) >= >
c               Bthresconcen)) then
c                   weight=
c                   float(counter2(I,J))**(Bpower-1.0)

c                   outH=
c                   Const*Rate*Time*(grad*0.001)*weight*
c                   (1.0-fraction)
c                   DeltaH = -(cover(I,J) + outH)
c                   basalthk(I,J) = basalthk(I,J) - outH

c                   if (basalthk(I,J) <= Bthresthk) then
c                       basalthk(I,J) = 0.0
c                       geology(I,J) = 0
c                       cover(I,J) = Z(I,J) + DeltaH
c                       BotCount(I,J) = counter2(I,J)
c                       write(250,800) J, I, counter2(I,J), T
c                   endif
c                   else

```

```

        DeltaH = -cover(I,J)

        endif

c           If Material is being Deposited NOT Eroded

        else

            cover(I,J) = cover(I,J) + DeltaH

        endif

        Z(I,J) = Z(I,J) + DeltaH
        modify(I,J) = modify(I,J) + DeltaH
        inH = inH - DeltaH

        I = I + AmaxG
        J = J + BmaxG

c           ENDDO of follow Waterbot calculate Sed. Trans.
20         continue
         enddo

c           ENDDO to hit each Row,Column position in Z array
30         continue
         enddo

c           Write output to output files
         open(unit=T*1, file=filename(T,5), status='unknown')
         open(unit=T*3, file=filename(T,2), status='unknown')
         open(unit=T*5, file=filename(T,1), status='unknown')
         open(unit=T*7, file=filename(T,4), status='unknown')
         open(unit=T*9, file=filename(T,3), status='unknown')
         open(unit=T*11, file=filename(T,6), status='unknown')

         do I = north, south, -1
             write(T*1,200) (counter2(I,J), J = west, east)
             write(T*3,400) (Z(I,J), J = west, east)
             write(T*5,400) (modify(I,J), J = west, east)
             write(T*7,400) (basalthk(I,J), J = west, east)
             write(T*9,400) (cover(I,J), J = west, east)
             write(T*11,400) (BotCount(I,J), J = west, east)
         enddo

         do file = T*1, T*11, T*2
             close(unit=file)
         enddo

```

```

c      Lower the Western boundary by 2cm/1000 yrs.
!
!      do I = south, north
!          Z(I,west) = Z(I,west) - ((0.013/1000.0)*Time)
!          modify(I,west) = modify(I,west) - ((0.013/1000.0)*Time)
!
!      enddo

c      ENDDO to evolve landscape through time
enddo

c      write XYX ASCII file for import into ERMapper
!      open(unit=110, file='ERMapperZ.out', status='unknown')

!
!      do I = south, north
!          do J = west, east
!              write(110,600) float(J*30), float(I*30), Z(I,J)
!          enddo
!      enddo
!
!      close (unit=110)

close(250)

200  format (1X, 5000I12)
400  format (1X, 5000E15.8E2)
600  format (1X, 5000F12.4)
800  format (1X, 2I6, 1I12, I6)

return
end

```

```

subroutine gradient(Z,DelG,south,north,west,east)

*$noex
implicit none

c Declaration of variables
include 'E8ArraySize.fi'

integer :: south, north, west, east      !Location of map boundaries
integer :: I,J                           !Row (I) and Column (J) indices

c Position Indices
integer :: A           !Scan Row
integer :: B           !Scan Column
integer, parameter :: scan = 1   !Defines size of box to scan gradients
integer :: AmaxG        !Holds Scan Row of maximum gradient
integer :: BmaxG        !Holds Scan Column of maximum gradient

c Topography variables, Directionality variables
real :: DeltaZ       !Elev. difference b/t current cell and neighbor cells
real, dimension(MaxR,MaxC) :: Z          !Elevation matrix
real, dimension(MaxR,MaxC) :: DelG       !Gradient matrix
real :: max           !Holds value of maximum gradient
                           !(using RHO8) to neighbor cells
real :: length         !Distance to lowest neighbor cell
real :: grad            !Gradient to lowest neighbor cell
real :: space = 30.0    !Horizontal resolution of USGS DEMs (m)

write (*,*) 'Calculating Gradients...'

do I = south+1, north-1
    do J = west+1, east-1

        AmaxG = 0
        BmaxG = 0
        max = 0.0

c Find Maximum gradient
        do A = -scan, scan, 1
            do B = -scan, scan, 1

c Calculate grad for scan .EQ. 1
                if ( (B .EQ. 0 .AND. (A .EQ. +scan .OR.
                    A .EQ.-scan)) .OR. (A .EQ. 0 .AND. (B .EQ. ->
                    scan .OR. B .EQ. +scan))) then

                    DeltaZ = (Z(I,J)-Z(I+A,J+B))/30.0

                else


```

```

DeltaZ = (Z(I,J)-Z(I+A,J+B))/42.42641

        endif

c          Check for maximum DeltaZ
if(DeltaZ .GT. max) then
        max = DeltaZ

        AmaxG = A
        BmaxG = B
        endif

c          End neighbor DO LOOPS

        enddo
        enddo

c          Calculate Gradient to lowest elevation

        if (AmaxG .EQ. 0 .and. BmaxG .EQ. 0) then

                length = 1.0
        else
                length =
                (SQRT((float(AmaxG))**2+(float(BmaxG))**2))
                *(space)
        endif

        grad = (Z(I,J)-Z(I+AmaxG,J+BmaxG)) / length

        DelG(I,J) = grad

        enddo
        enddo

c          Write output of DelG to output file
open(unit=10, file='MaxG.out', status='unknown')

        do I = north, south, -1
                write(10,20) (DelG(I,J), J = west, east)
        enddo

        close (unit=10)
20      format (1X, 5000E15.8E2)

        return
end

```



```

subroutine channel1(Z,stream,counter1,step1,step2,n,south,north,
>      west,east,Wro,Wco)

*$noex
implicit none

c Declaration of variables
include 'E8ArraySize.fl'

c Two-D ARRAYs (Matrix of Data)
real :: Z(MaxR,MaxC) !2D array of elevation data
!Z is created in the ASSEMBLE subroutine
integer :: counter1(MaxR,MaxC)           !2D array containing number of
!WATERBOTS thru each cell

!COUNTER1 is calculated/updated in the CHANNEL1 subroutine

c One-D ARRAYs
real :: step1(NumCells) !1D array of random numbers b/t 1, NumCells
!used to sort random waterbot drop sequence
!STEP1 is created in the RANORDER
integer :: step2(NumCells)      !1D array of unique integer location
!(translatable to Row,Column) elevation
!STEP2 is created in the RANORDER
integer :: stream(NumCells,3)   !Contains (Column,Row,Integer Location
!of next step position)

!STREAM is created in the RANORDER subroutine

c Array indices
integer :: I                      !Row index
integer :: J                      !Column index

c DEM variables Size, Dimensions, Etc.
integer :: south !Value of Row (+ve from south) of Southern Boundary
integer :: north !Value of Row (+ve from south) of Northern Boundary
integer :: west  !Value of Row (+ve from west) of Western Boundary
integer :: east  !Value of Row (+ve from west) of Eastern Boundary
integer :: n    !Number of elevation cells in the Z array

!Calculated in RANORDER subroutine
integer :: Wro !Number of Rows in working Z array, RANORDER
integer :: Wco !Number of Columns in working Z array, RANORDER

integer :: M      !Index to drop waterbot on each cell
integer :: next   !Counter/placeholder in stream array

c Call subroutine spatial to generate 1D array of elevations
c Subroutine 'ranorder' is required for both Subroutines 'transport'
call ranorder(step1,step2,stream,n,south,north,west,east,

```

```

>      Wro,Wco)

c   Call subroutine network to calculate and store position of
c   maximum gradient
call network(Z,stream,south,north,west,east,
>      Wro,Wco)

write (*,*) 'Delineating Stream Network (Channel1)...'

c   initialize counter array to zero
do I = south, north
    do J = west, east
        counter1(I,J) = 0

    enddo
enddo

c   Create array with appropriate fluvion count
do M = 1, (Wro*Wco)

    next = M

    do while (next .NE. 0)

        J = stream(next,1)
        I = stream(next,2)

        counter1(I,J) = counter1(I,J) + 1

        next = stream(next,3)

    enddo

enddo

c   Write output of DelG to output file
open(unit=10, file='Channel1.out', status='unknown')

do I = north, south, -1
    write(10,20) (counter1(I,J), J = west, east)
enddo

close (unit=10)
20  format (1X, 5000I12)

return
end

```

```

subroutine shade(Z,shadow,space,south,north,west,east)

implicit none
c Declaration of variables
c Defining common ARRAY dimensions
include 'E8ArraySize.fi'

c Two-D ARRAYs (Matrix of Data)
real :: Z(MaxR,MaxC) !2D array of elevation data
!Z is created in the ASSEMBLE subroutine
real :: Shadow(MaxR,MaxC) !2D array containing the Relief info

!SHADOW is created/calculated in the SHADE subroutine

c DEM variables Size, Dimensions, Etc.
integer :: south !Value of Row (+ve from south) of Southern Boundary
integer :: north !Value of Row (+ve from south) of Northern Boundary
integer :: west !Value of Row (+ve from west) of Western Boundary
integer :: east !Value of Row (+ve from west) of Eastern Boundary

c Array indices
integer :: I !Row index
integer :: J !Column index
real :: space

real :: grad !elevation difference in direction of sun
real :: slangle !Slope angle in direction of sun
real :: slnormal !Slope normal angle
real :: epsilon !Slope angle in direction of sun
real :: incidence !Angle of incidence
real :: sunangle !Sun angle (0 Degrees is Eastern Horizon)
real :: pi = 3.142 !Value of PI
real :: conv !Conversion from degrees to radians
real :: exaggerate !Amount of verticle exaggeration to add to elev.

write (*,*) 'Creating Shaded Relief Image Data...'

conv = pi/180.0
sunangle = (11/12.0)*pi
exaggerate = 1.0

c West/East Do Loops
do I = south, north
    do J = west, (east-1)

        grad = (Z(I,J+1)-Z(I,J))*exaggerate
        slangle = ATAN(grad/space)
        slnormal = slangle + (pi/2.0)

```

```

        epsilon = slangle
        incidence = sunangle - slnormal

        shadow(I,J) = 1.0 / ( 1.0 + (COS(epsilon)/COS(incidence)) )

        if (shadow(I,J) .LT. 0.0) then
            shadow(I,J) = 0.0
        endif
        if (shadow(I,J) .GT. 0.7) then
            shadow(I,J) = 0.7
        endif

        enddo
    enddo

c      Write output of DelG to output file
      open(unit=10, file='Shaded.out', status='unknown')

      do I = north, south, -1
          write(10,20) (shadow(I,J), J = west, east)
      enddo

      close (unit=10)
20    format (1X, 5000E15.8E2)

      return
end

```

E8ArraySize.fi

```
c      Declaration of variables
c      Defining common ARRAY dimensions
      integer, parameter :: MaxC = 1200      !Dimension of elev array in cols.
      integer, parameter :: MaxR = 1000      !Dimension of elev array in rows
      integer, parameter :: NumCells = MaxR*MaxC  !Number of elevations
!cells expected in DEM
```

E8SubTrans.fi

```
c      Waterbot characteristics/information
real :: Rolls           !Number os step the waterbot has already taken
real :: step = 2.0       !Number os steps to build to full Sediment
                        !Capacity
real   :: Gpower = 1.0  !Power of discharge for pediment surface
real   :: Bpower = 1.1  !Power of discharge for basalt surface
real   :: weight

c      Array indices
integer :: I             !Row index
integer :: J             !Column index

c      Variables used in calculation of Waterbot Sediment Capacity
real, parameter :: Totyears     = 5.0E04      !Total number of years
                                              !to evolve the landscape
real, parameter :: Time    = 5.0E04      !Time (yrs) of each successive
                                         !time step
real, parameter :: Rate     = 0.1        !Time (yrs) of each successive
                                         !time step
real, parameter :: Const    = 0.003      !Time (yrs) of each successive
                                         !time step
```

E8TransVar.fi

```
c      Declaration of local variables in Subroutine TRANSPORT
c      Do Loop Indices
integer :: T      !Used in Do Loop to evolve landscape thru time
integer :: S      !Used in Do Loop to hit each Row,Column with Waterbot

c      Position Indices
integer :: A          !Scan Row
integer :: B          !Scan Column
integer :: C          !Index for DeltaZ array
integer, parameter :: scan = 1 !Defines size of box to scan gradients
integer :: AmaxG      !Holds Scan Row of maximum gradient
integer :: BmaxG      !Holds Scan Column of maximum gradient

c      Sediment Capacity Variables
real :: inH          !Thickness of material comming into cell (+ve)
real :: DeltaH        !Thickness to erode/deposit from current cell (-ve for
                     !erosion)
real :: length        !Distance b/t current cell and next step
real :: grad           !Gradient b/t current cell and next step

c      Topography variables, Directionality variables
real, dimension(9,3) :: DeltaZ    !Elev. difference b/t current cell and
                     !neighbor cells
real :: Delta          !Calculated difference in elevation of current cell
                     !and neighbor
real :: max            !Holds value of maximum gradient (using RHO8)
                     !to neighbor cells
real :: min            !Holds value of lowest neighbor
real :: maxdelZ        !Holds value of true maximum difference in
                     !elevation b/t cells
real :: rho8            !Fairfields (1991) directionality variable
integer :: Seed          !Random seed variable for random number
                     !generation
real    :: ran2          !Random number generator 2 (+ve input)
real    :: random         !Random number b/t 0.0 and 1.0
```

E8variables.fi

c Declaration of variables
c Defining common ARRAY dimensions
include 'E8ArraySize.fi'

c Two-D ARRAYS (Matrix of Data)
real :: Z(MaxR,MaxC) !2D array of elevation data
!Z is created in the ASSEMBLE subroutine
real :: cover(MaxR,MaxC) !2D array of thickness of alluvial cover

!COVER is created in the ALLUVIUM subroutine
real :: modify(MaxR,MaxC) !2D array of amount of elev change (+/-)

!MODIFY is calculated/updated in the TRANSPORT subroutines
integer :: counter1(MaxR,MaxC) !2D array containing number of
!WATERBOTS passing thru each cell

!COUNTER1 is calculated/updated in the CHANNEL1 subroutine
integer :: counter2(MaxR,MaxC) !2D array containing number of
!WATERBOTS passing thru each cell

!COUNTER2 is calculated/updated in the TRANSPORT subroutines
real :: DelG(MaxR,MaxC) !2D array containing the maximum
!gradient value of 8 neighbors

!DELG is created/calculated in the GRADIENT subroutine
real :: Shadow(MaxR,MaxC) !2D array containing the Shaded Relief

!SHADOW is created/calculated in the SHADE subroutine
integer :: geology(MaxR,MaxC) !GEOLOGY contains information on the
!type of material present in cell

!GEOLOGY is created in the LAVA subroutine
real :: basalthk(MaxR,MaxC) !BASALTHK contains the thickness of
!the Basalt in the Cell

!BASALTHK is created in the LAVA subroutine
real :: basaltbot(MaxR,MaxC) !BASALTBOT contains the elevation to
!the bottom of the basalt

!BASALTBOT is created in the LAVA subroutine

c One-D ARRAYS
real :: step1(NumCells) !1D array of random numbers b/t 1, NumCells
!used to sort and order random waterbot drop

!STEP1 is created in the RANORDER subroutine

```
integer :: step2(NumCells)      !1D array of unique integer location
                                         !(translatable to Row,Column) of each
                                         !elevation
```

```
!STEP2 is created in the RANORDER subroutine
integer :: stream(NumCells,3)    !Contains (Column,Row,Integer Location
                                         !of next step position)
```

!STREAM is created in the RANORDER subroutine

c DEM variables Size, Dimensions, Etc.

```
integer :: south   !Value of Row (+ve from south) of Southern Boundary
integer :: north   !Value of Row (+ve from south) of Northern Boundary
integer :: west    !Value of Row (+ve from west) of Western Boundary
integer :: east    !Value of Row (+ve from west) of Eastern Boundary
integer :: n       !Number of elevation cells in the Z array
```

!Calculated in RANORDER subroutine

```
integer :: Wro     !Number of Rows in working Z array, RANORDER
integer :: Wco     !Number of Columns in working Z array, RANORDER
real :: space = 30.0    !Horizontal resolution of USGS DEMs (m)
```